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Kroening

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(54) **TWIST FOR CONNECTING ORTHOGONAL WAVEGUIDES IN A SINGLE HOUSING STRUCTURE**

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(51) **Int. Cl.**

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H01P 1/02	(2006.01)
H01P 3/123	(2006.01)
H01P 1/165	(2006.01)
H01P 1/18	(2006.01)
H01P 11/00	(2006.01)

(52) **U.S. Cl.**

CPC ***H01P 1/02*** (2013.01); ***H01P 1/022*** (2013.01); ***H01P 1/165*** (2013.01); ***H01P 1/182*** (2013.01); ***H01P 3/123*** (2013.01); ***H01P 11/00*** (2013.01); *Y10T 29/49016* (2015.01)

(58) **Field of Classification Search**

CPC H01P 1/02; H01P 1/022; H01P 1/025; H01P 1/027; H01P 1/165; H01P 3/123

USPC 333/249

See application file for complete search history.

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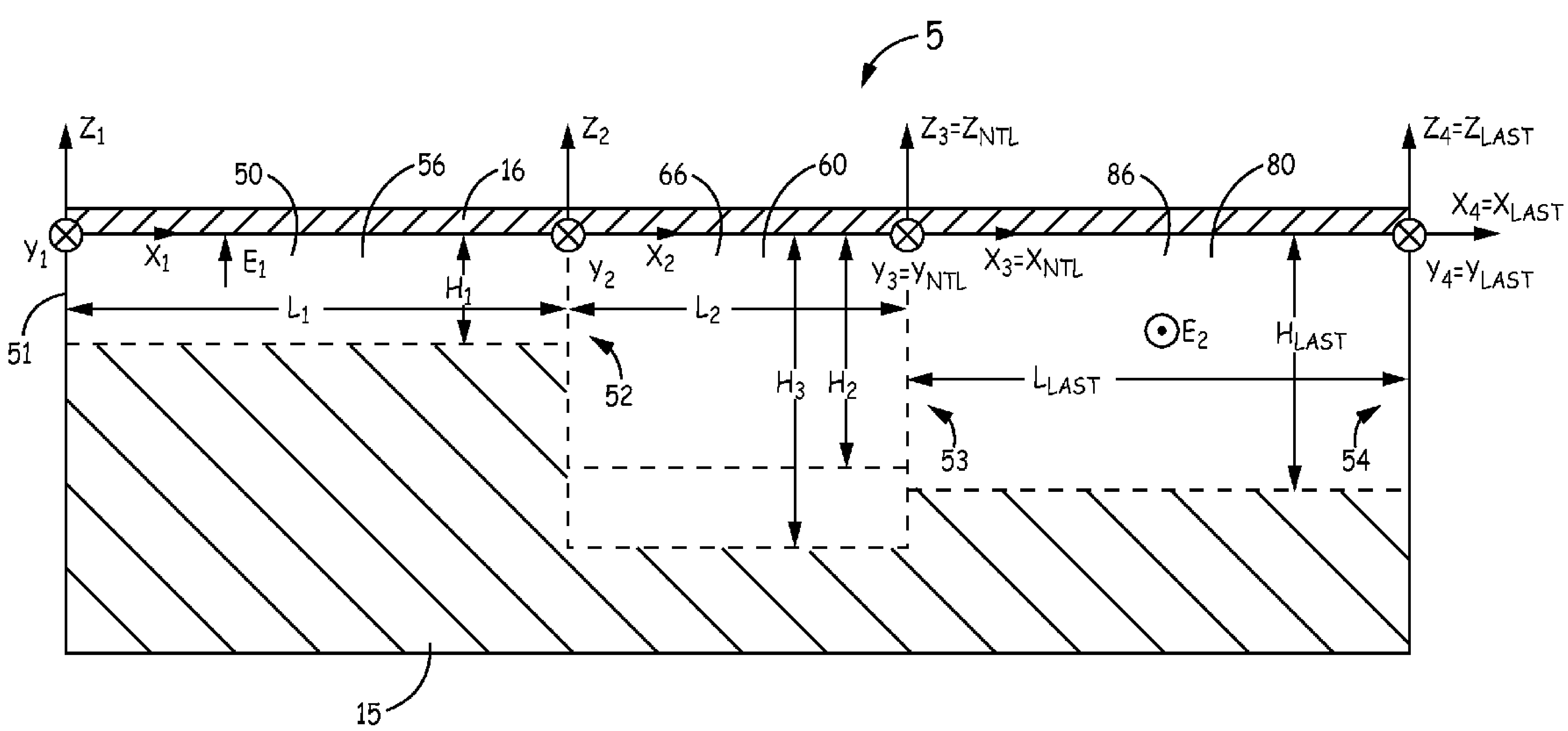
(57) **ABSTRACT**

A twist for coupling radiation between orthogonal waveguides is provided. The twist includes at least three cavities opening from at least one of a first X1-Y1 surface and a second X2-Y2 surface of a metal block. A first cavity has a first opening in a first Y-Z plane and a second opening in a second Y-Z plane offset from the first Y-Z plane by a first length. A second cavity shares the second opening with the first cavity and has a third opening in a third Y-Z plane offset from the second Y-Z plane by a second length and has at least two heights and at least two widths. A last cavity shares a next-to-last opening in a next-to-last Y-Z plane with a next-to-last cavity. The last cavity has a last opening in a last Y-Z plane offset from the next-to-last Y-Z plane by a last length.

16 Claims, 17 Drawing Sheets



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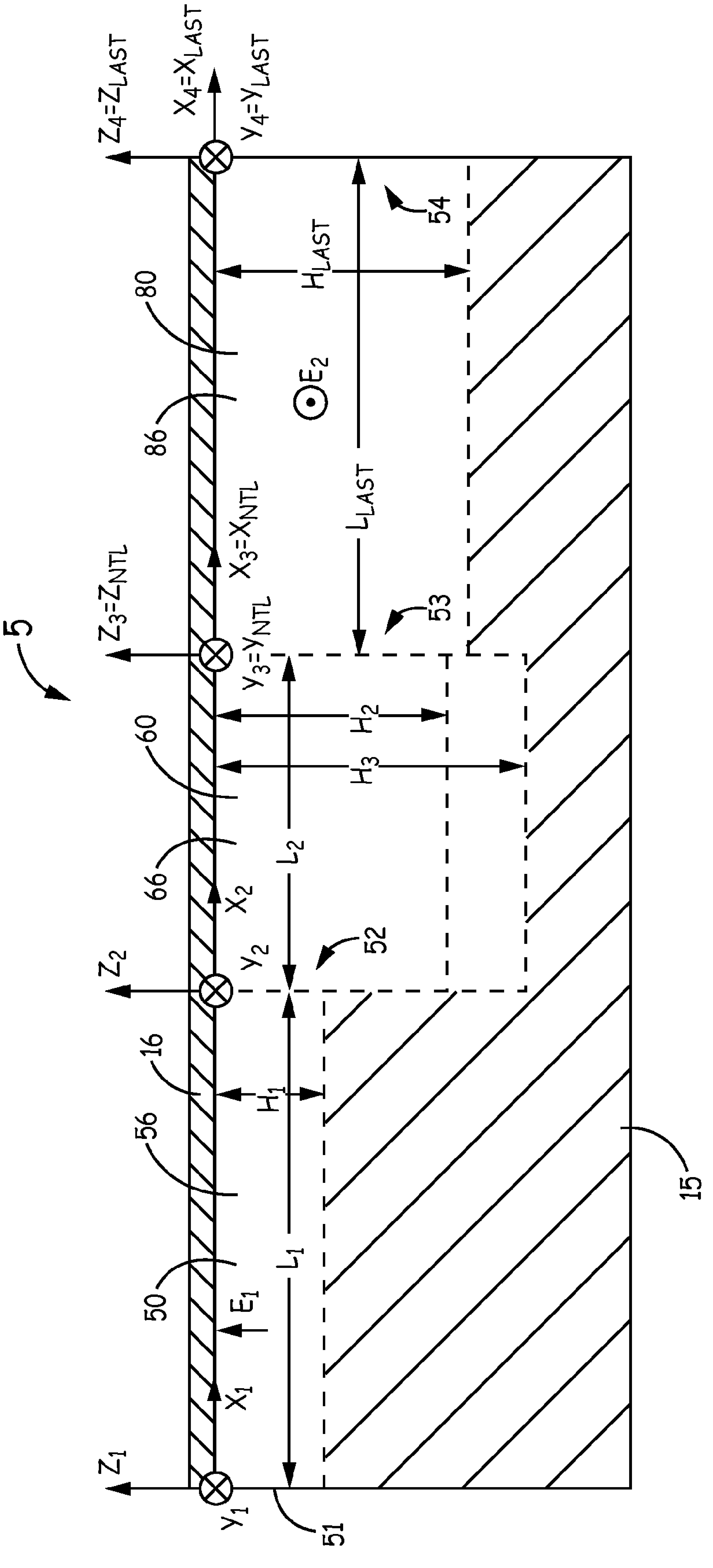

5
$Z_4=Z_{LAST}$
$X_4=X_{LAST}$
$Y_4=Y_{LAST}$
54
H_{LAST}
80
E_2
86
L_{LAST}
$X_3=X_{NTL}$
$Z_3=Z_{NTL}$
53
$Y_3=Y_{NTL}$
H_2
60
H_3
L_2
66
X_2
52
Y_2
Z_2
16
H_1
56
L_1
50
E_1
X_1
Z_1
Y_1
51
15

FIG. 1

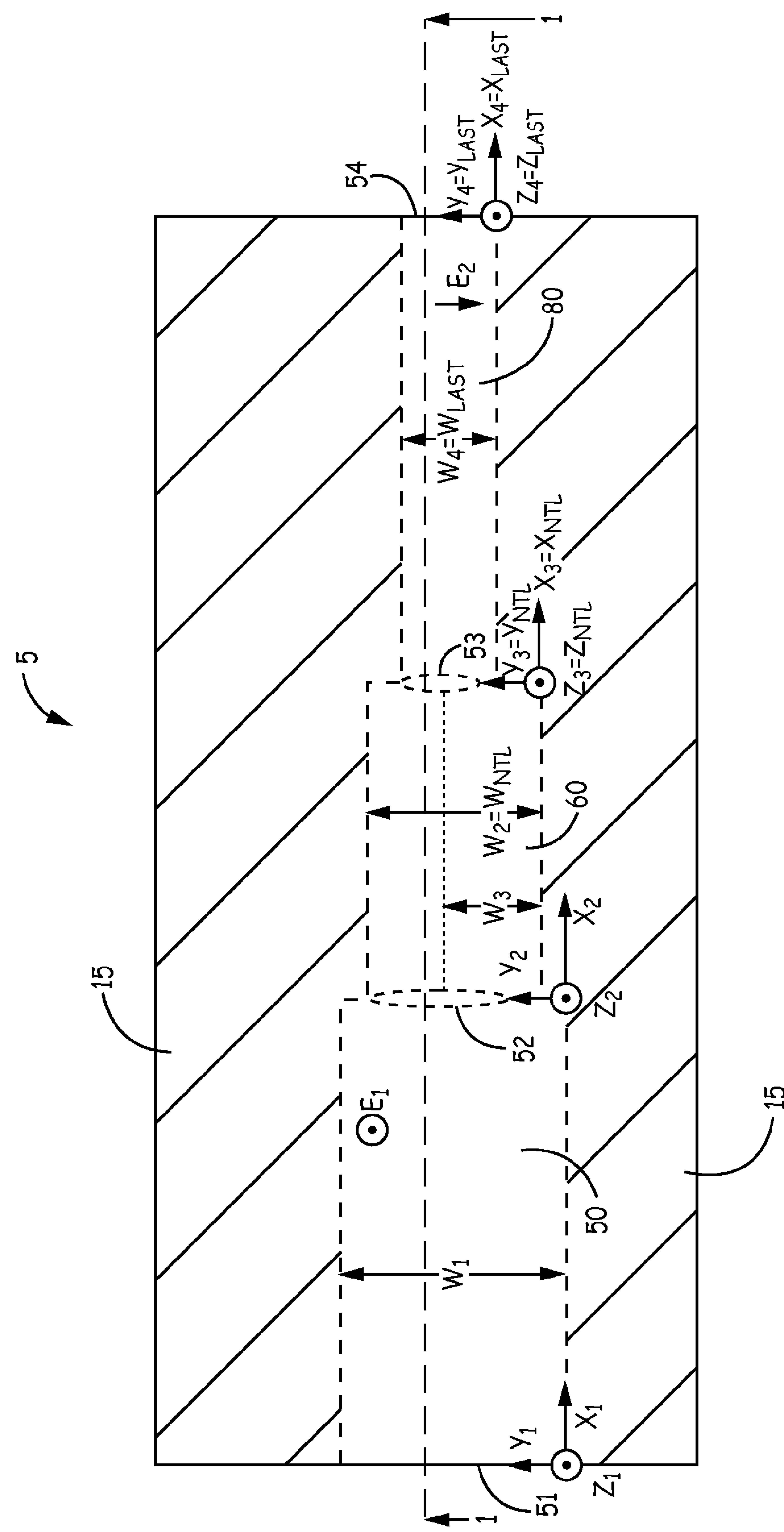

1
5
15
15
50
51
52
53
54
60
80
E1
E2
W1
W2=WNTL
W3
W4=WLAST
X1
Y1
Z1
X2
Y2
Z2
X3=XNTL
Y3=YNTL
Z3=ZNTL
X4=XLAST
Y4=YLAST
Z4=ZLAST

FIG. 2

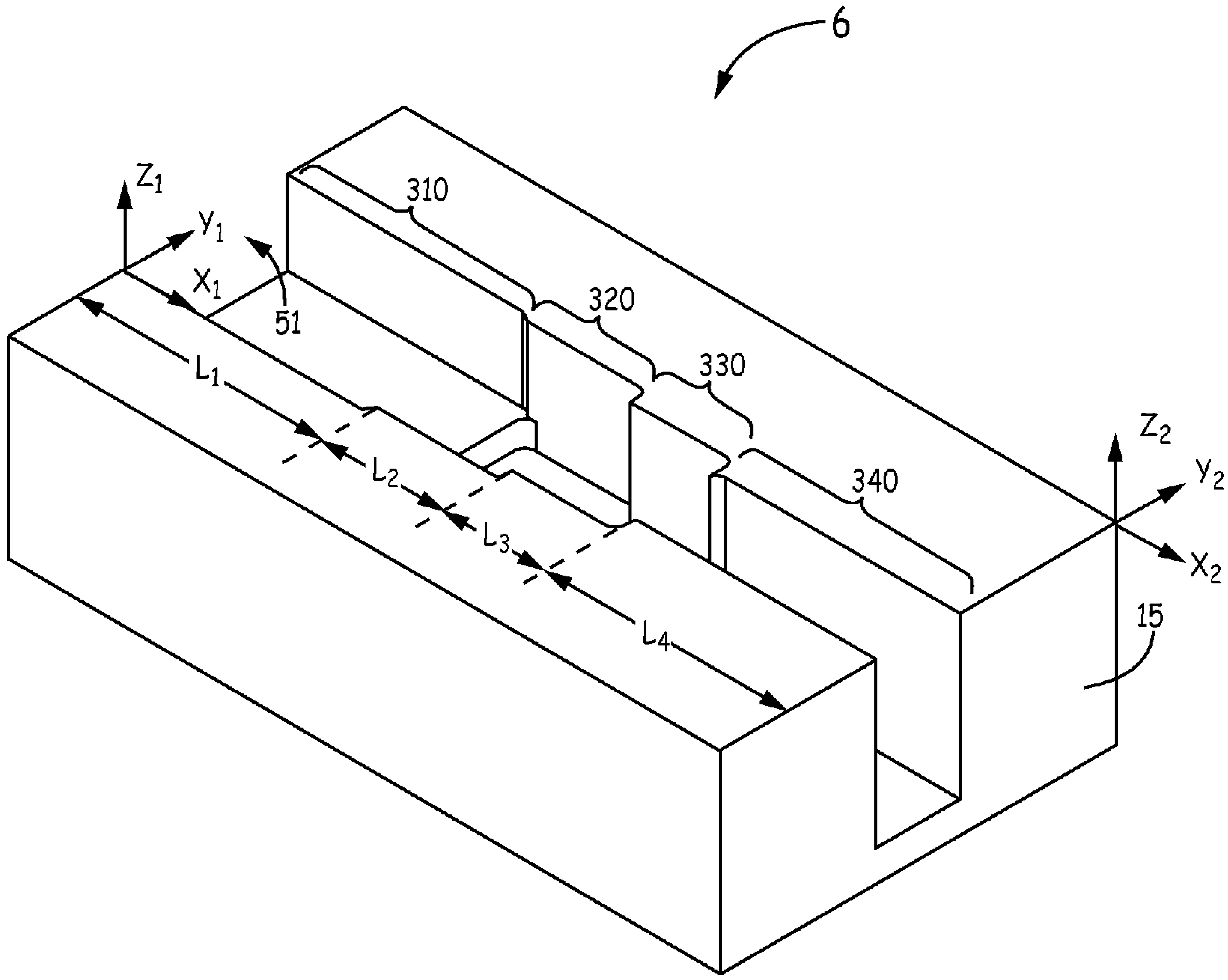


FIG. 3

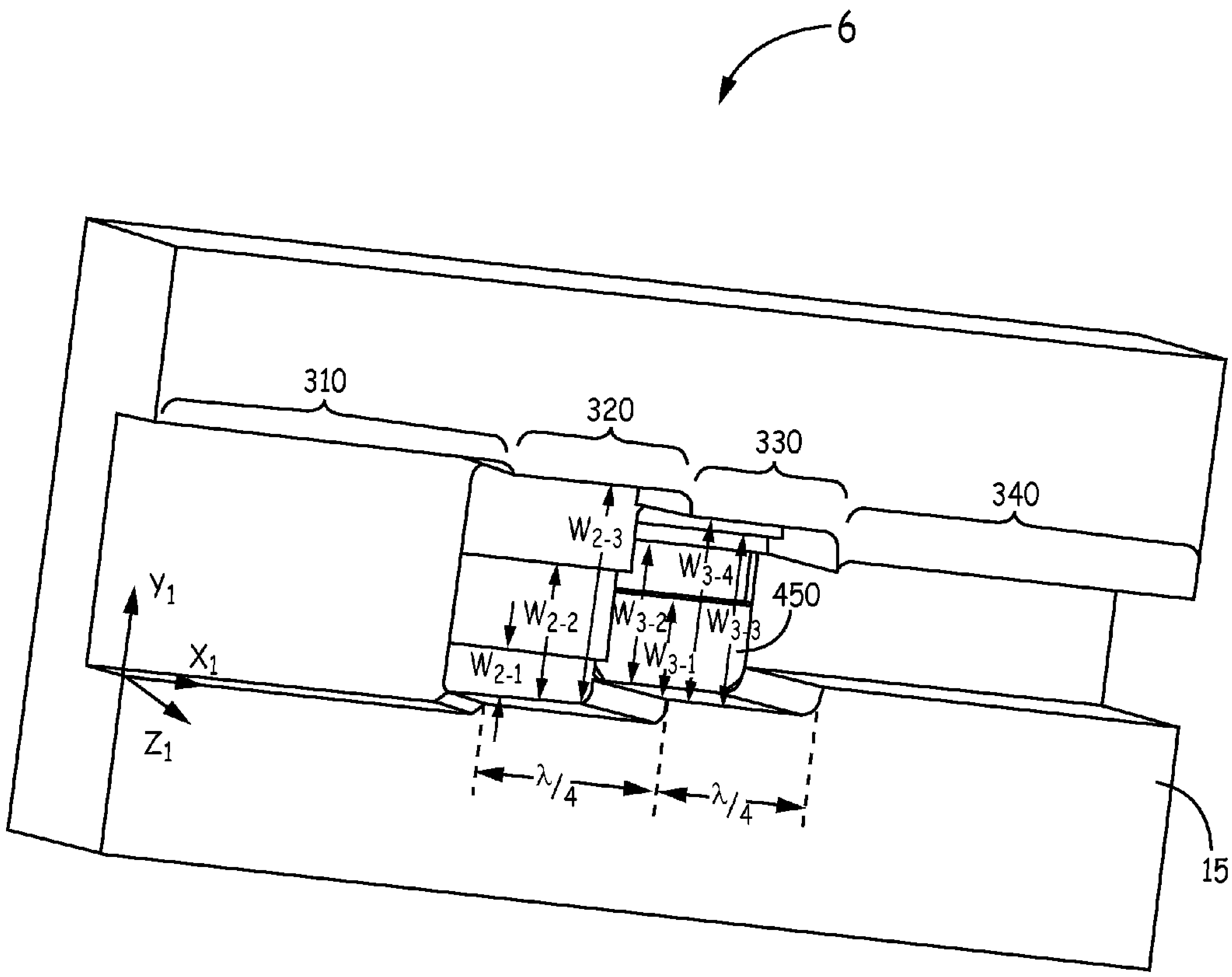


FIG. 4

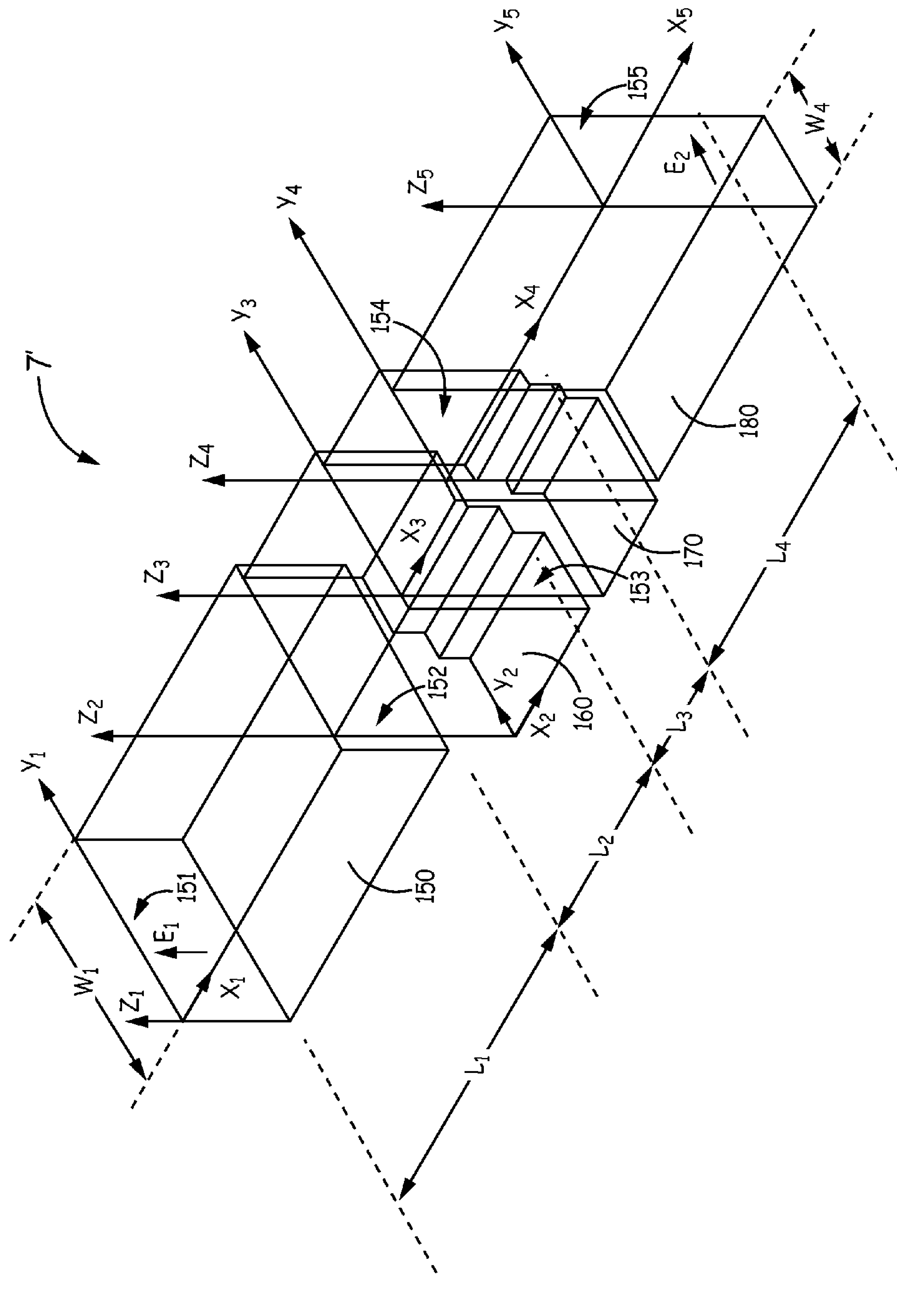

7'
150
151
152
153
154
155
160
170
180
X1
Y1
Z1
X2
Y2
Z2
X3
Y3
Z3
X4
Y4
Z4
X5
Y5
Z5
E1
E2
W1
W4
L1
L2
L3
L4

FIG. 5

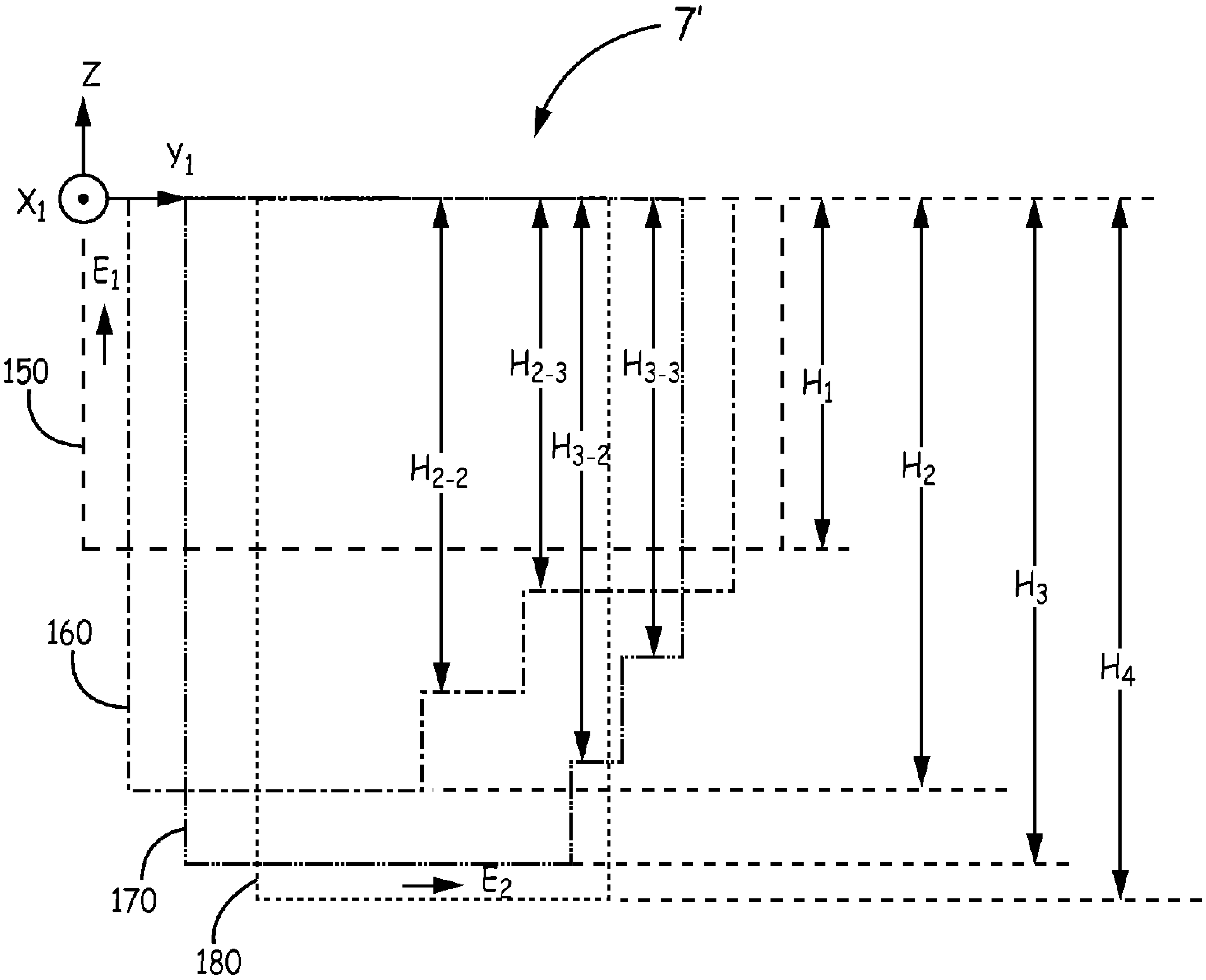


FIG. 6

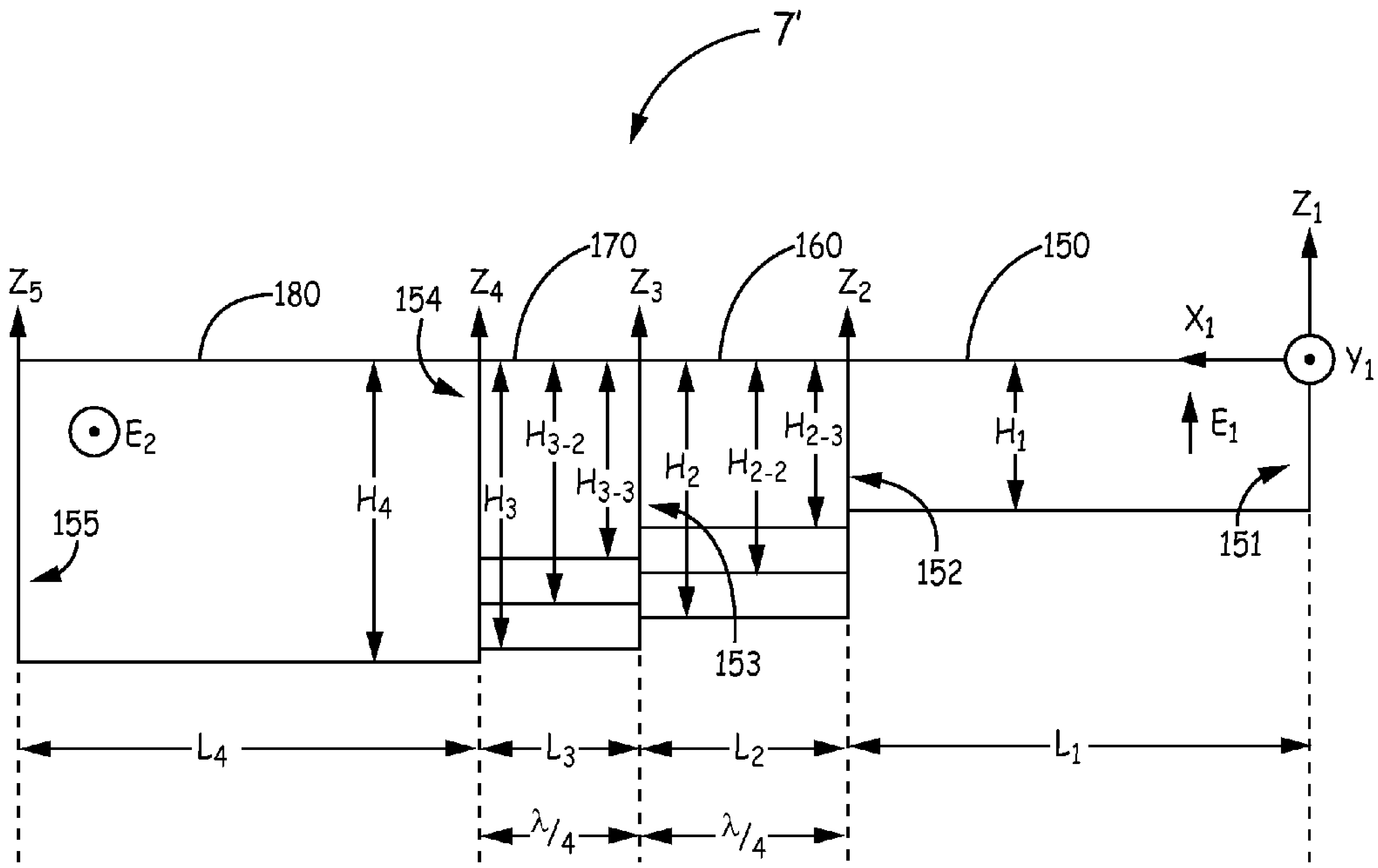

7'
Z_1
Z_5
180
154
Z_4
170
Z_3
160
Z_2
150
X_1
Y_1
E_2
E_1
H_4
H_3
H_{3-2}
H_{3-3}
H_2
H_{2-2}
H_{2-3}
H_1
155
153
152
151
L_4
L_3
L_2
L_1
$\lambda/_4$
$\lambda/_4$

FIG. 7

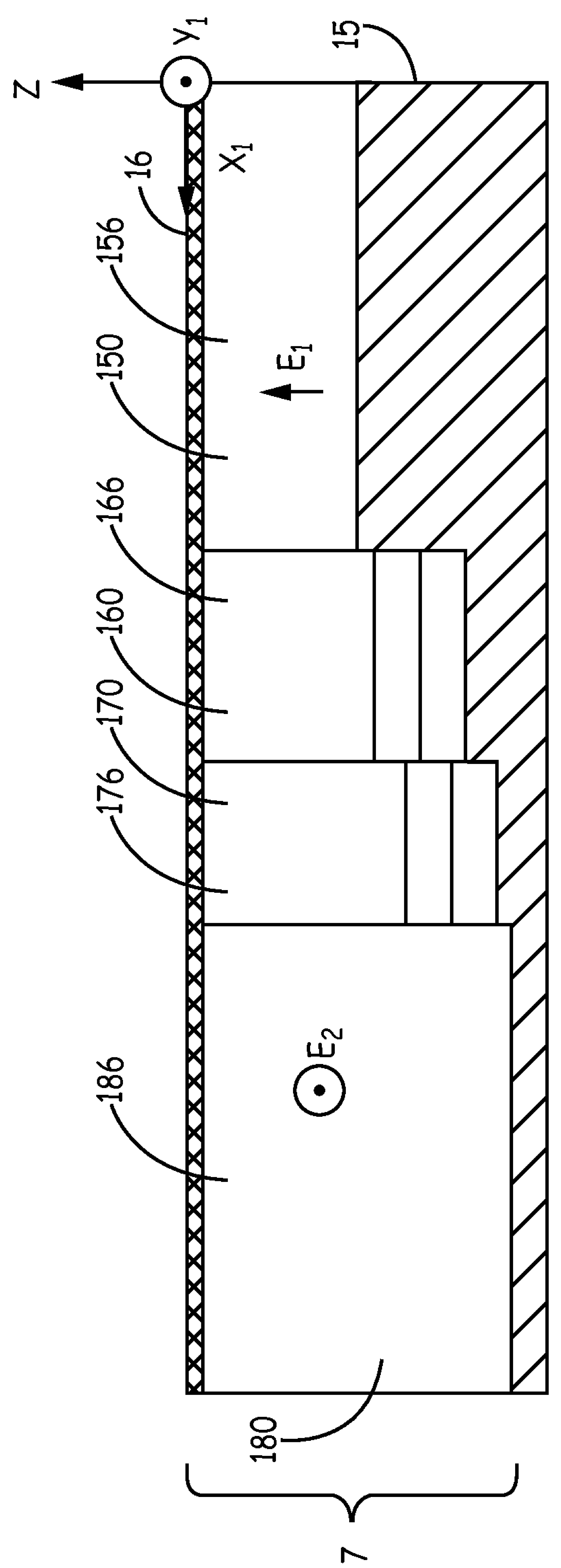


FIG. 8

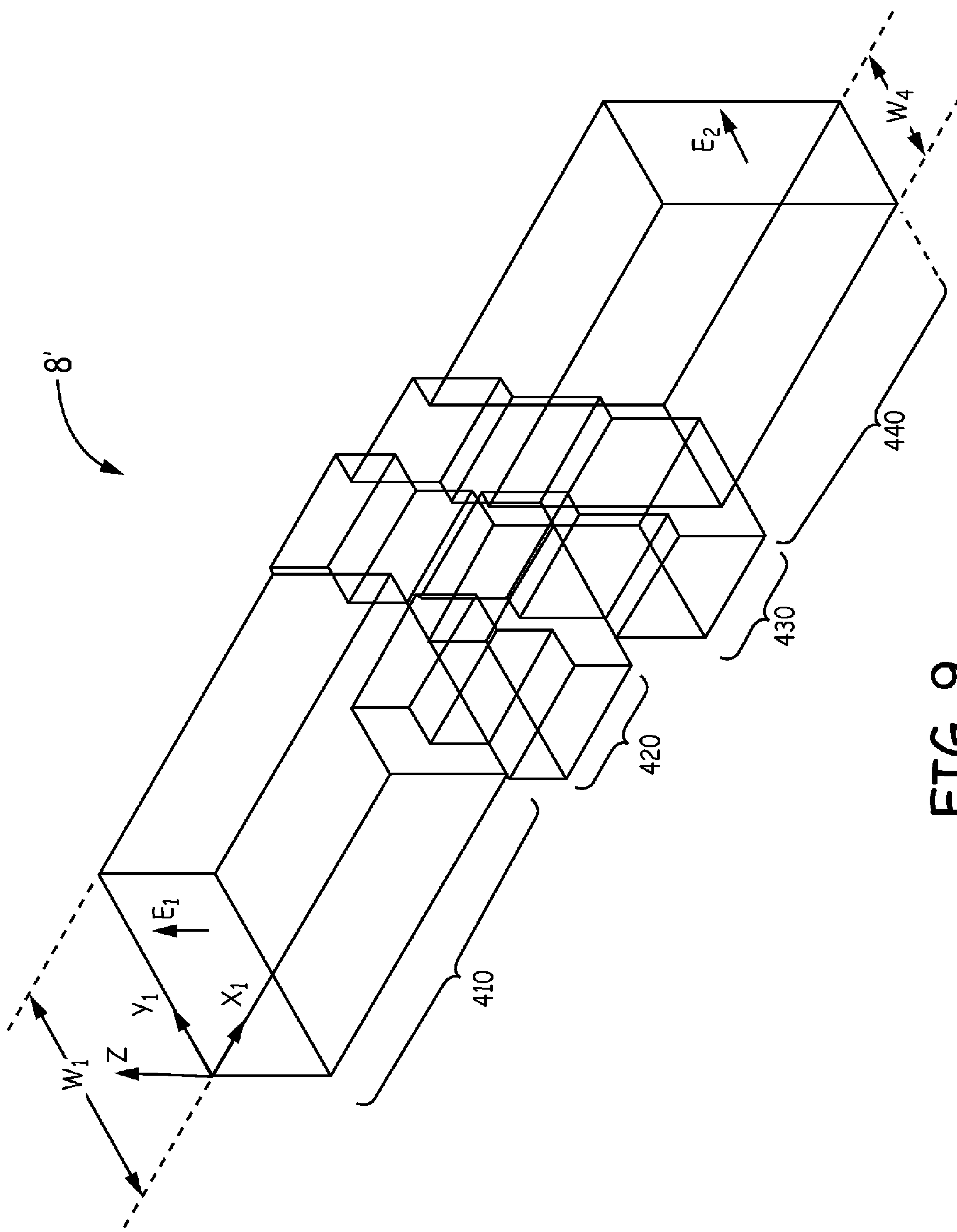


FIG. 9

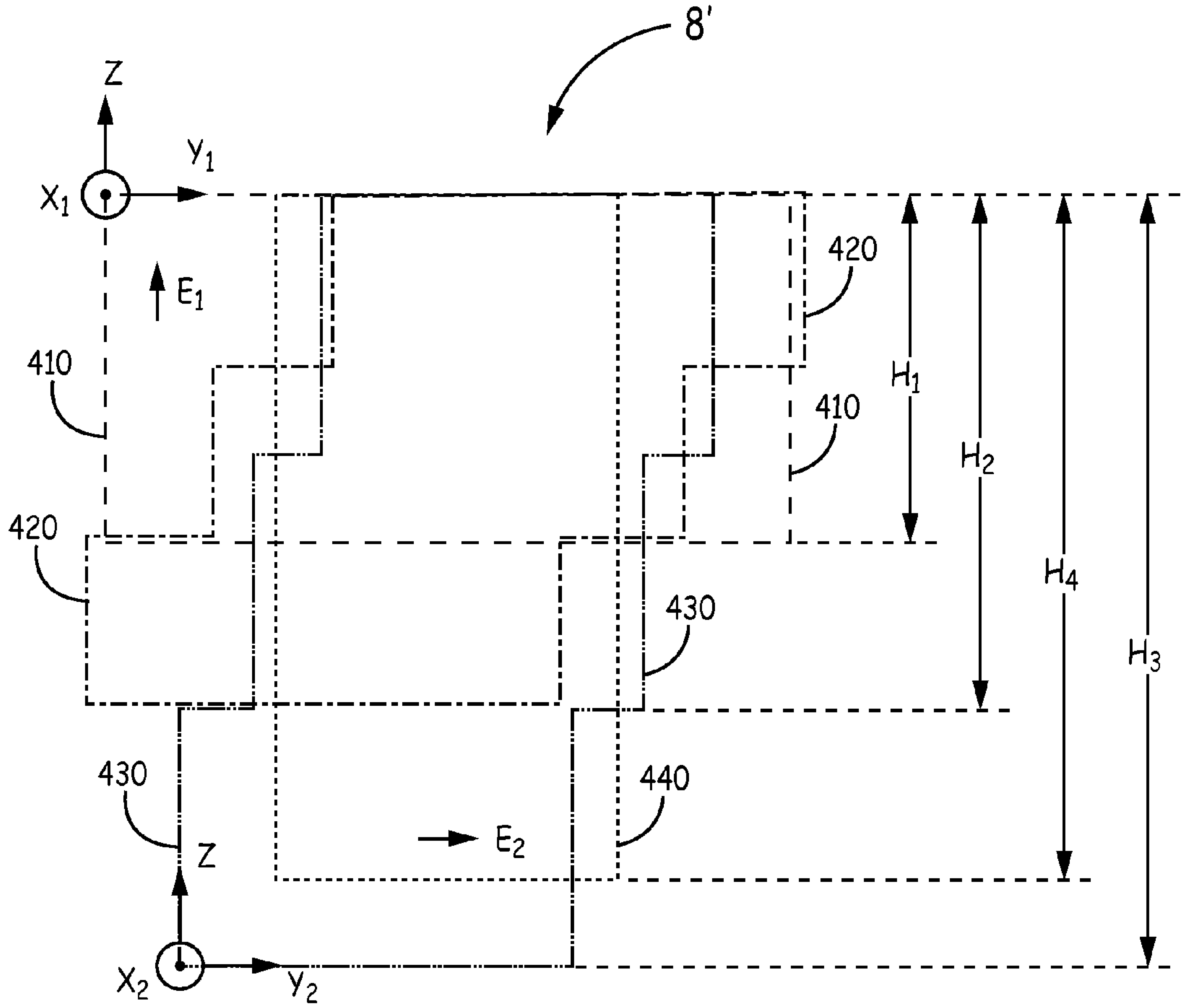
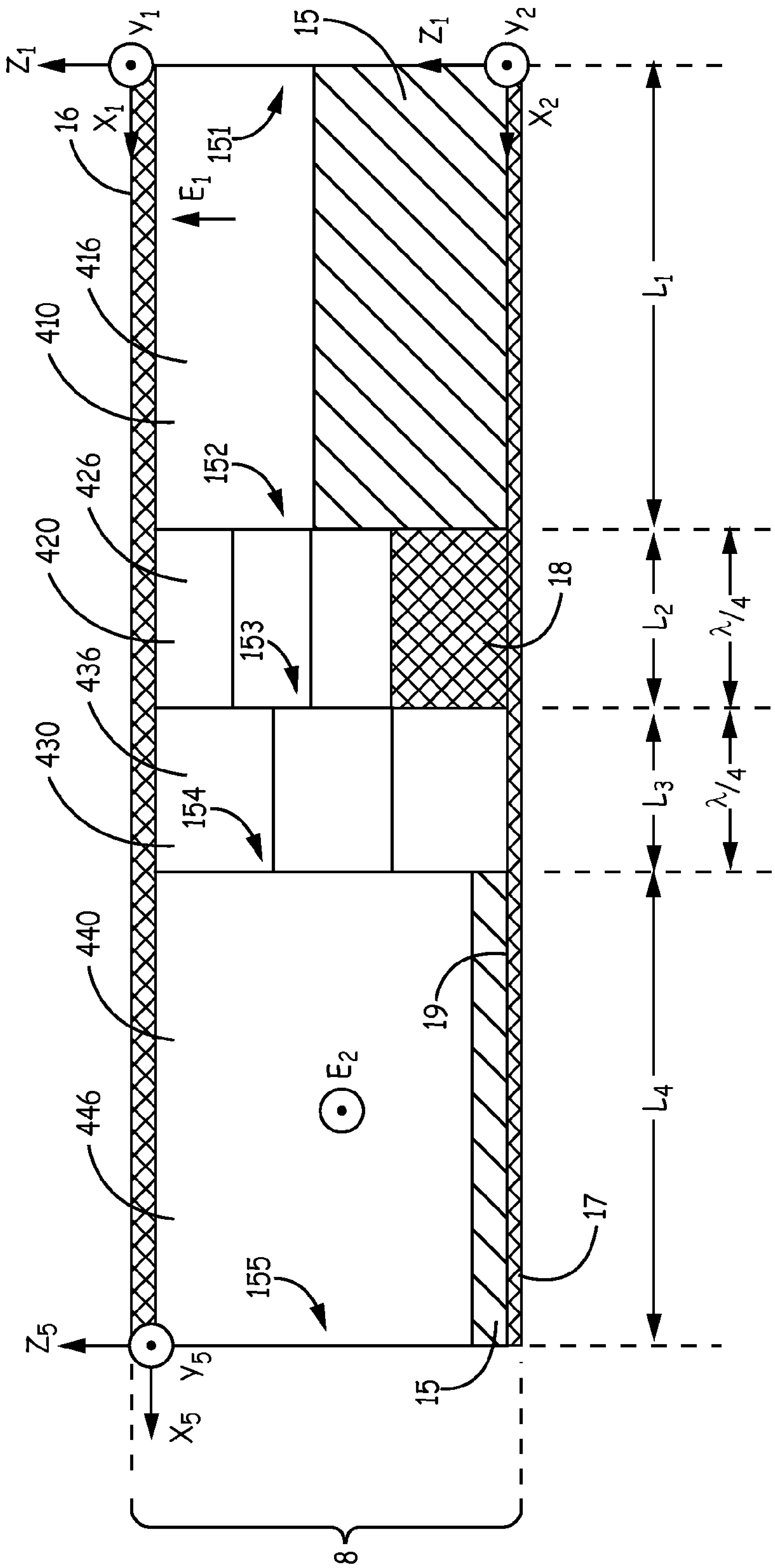


FIG. 10



Z_1
Y_1
X_1
Y_2
X_2
Z_5
Y_5
X_5
E_1
E_2
15
16
17
18
19
151
152
153
154
155
410
416
420
426
430
436
440
446
L_1
L_2
L_3
L_4
λ/4
λ/4
8

FIG. 11

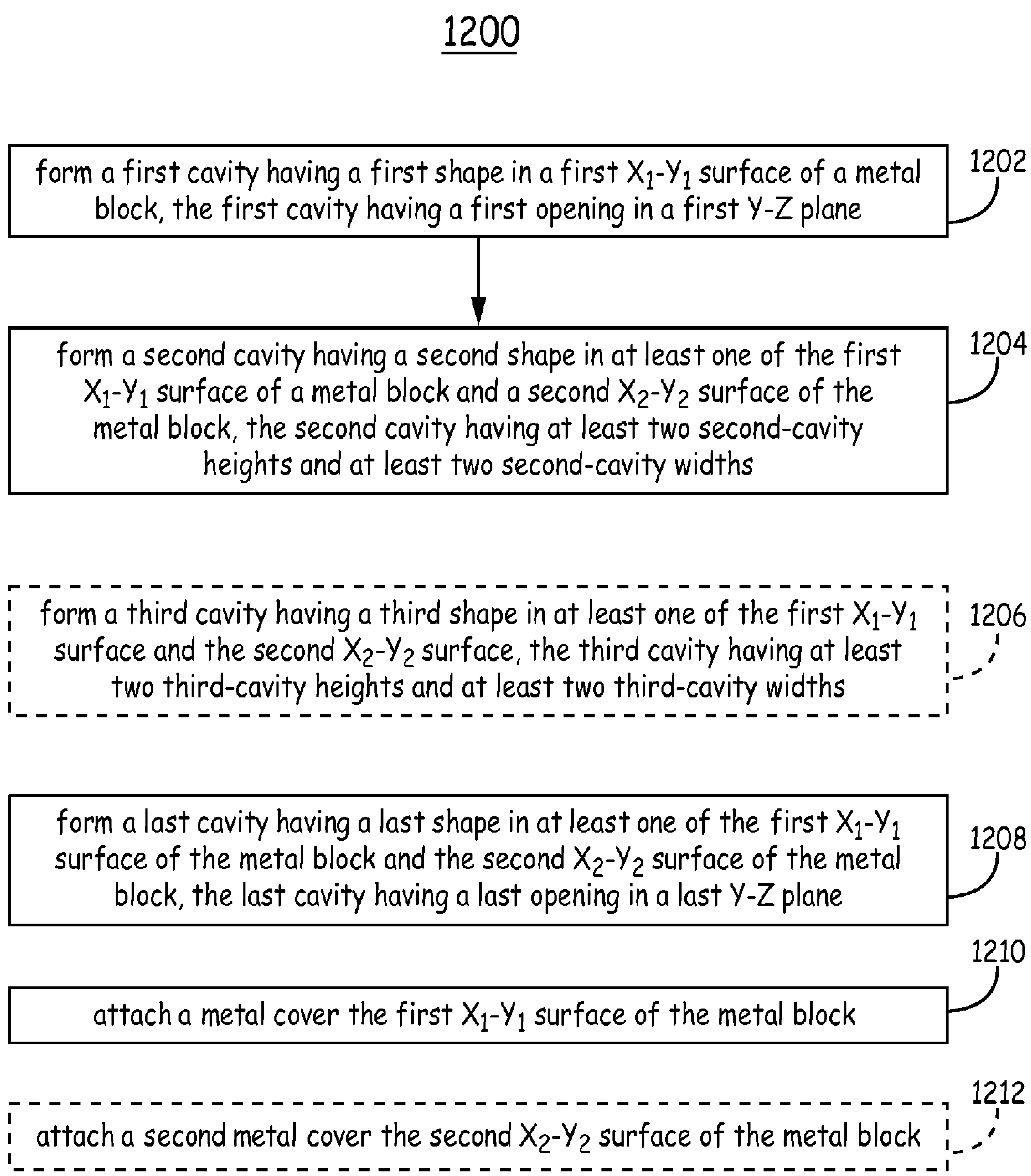

1200
form a first cavity having a first shape in a first X_1-Y_1 surface of a metal block, the first cavity having a first opening in a first Y-Z plane
1202
form a second cavity having a second shape in at least one of the first X_1-Y_1 surface of a metal block and a second X_2-Y_2 surface of the metal block, the second cavity having at least two second-cavity heights and at least two second-cavity widths
1204
form a third cavity having a third shape in at least one of the first X_1-Y_1 surface and the second X_2-Y_2 surface, the third cavity having at least two third-cavity heights and at least two third-cavity widths
1206
form a last cavity having a last shape in at least one of the first X_1-Y_1 surface of the metal block and the second X_2-Y_2 surface of the metal block, the last cavity having a last opening in a last Y-Z plane
1208
attach a metal cover the first X_1-Y_1 surface of the metal block
1210
attach a second metal cover the second X_2-Y_2 surface of the metal block
1212

FIG. 12

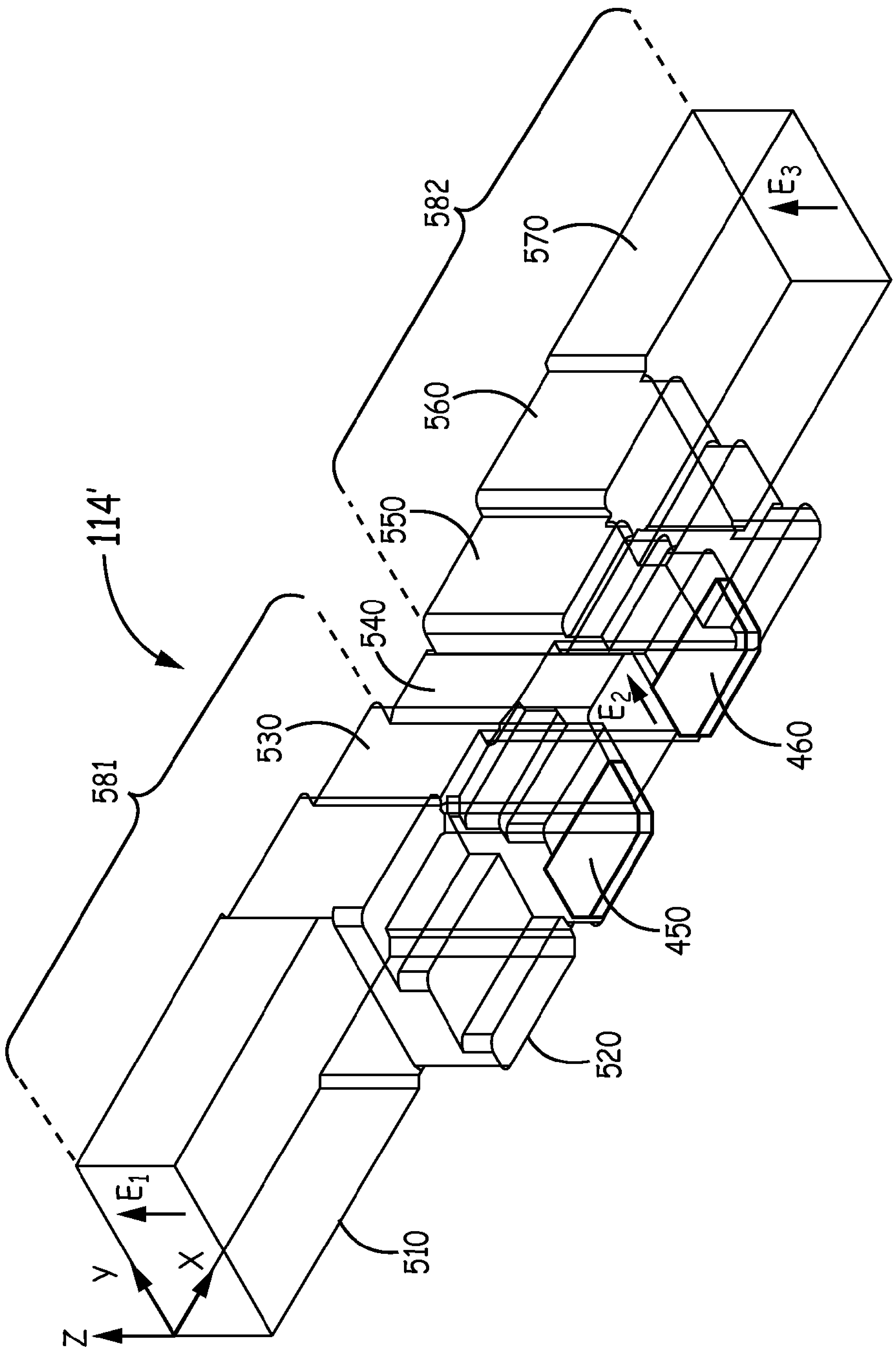


FIG. 13

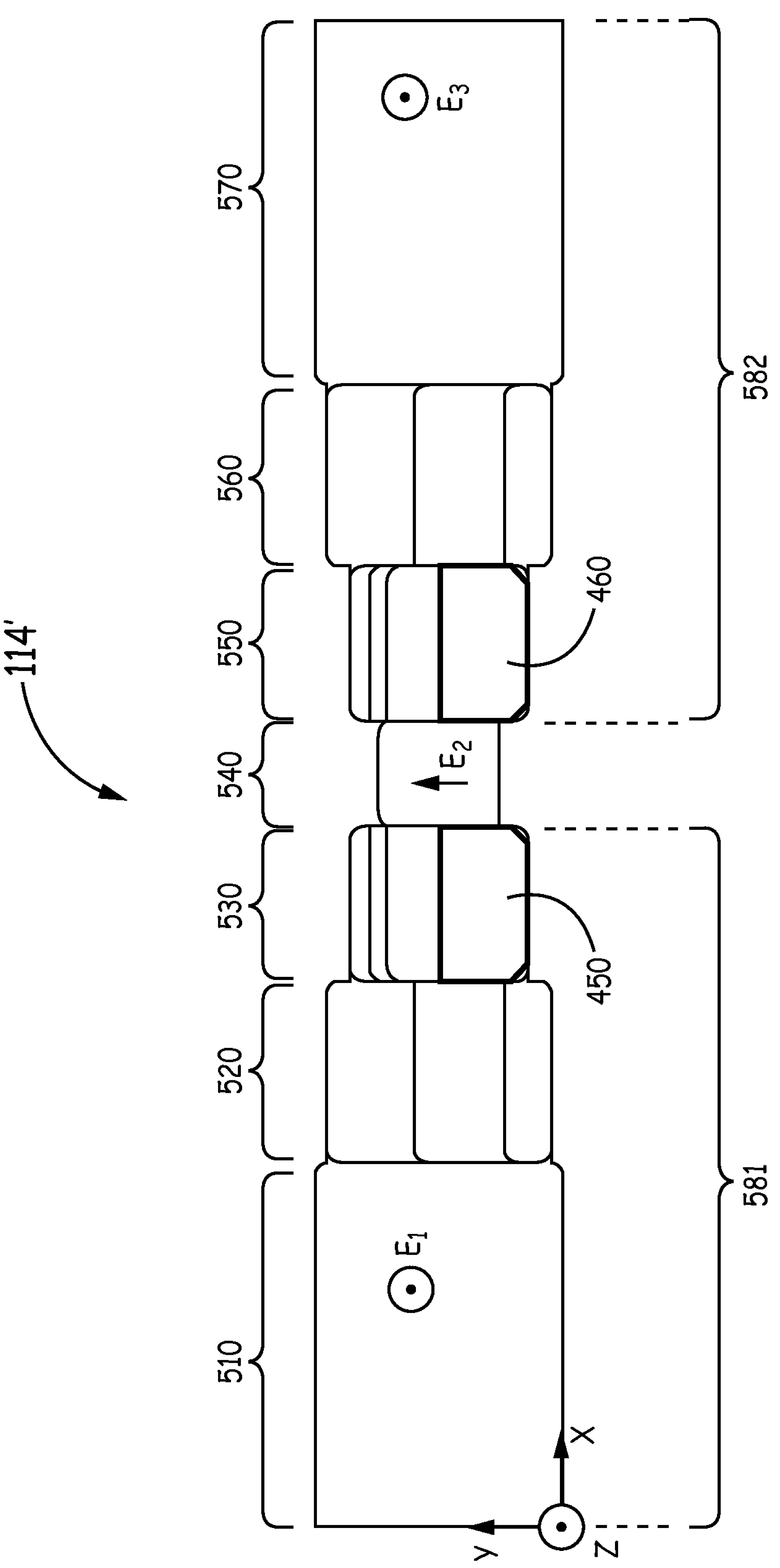


FIG. 14

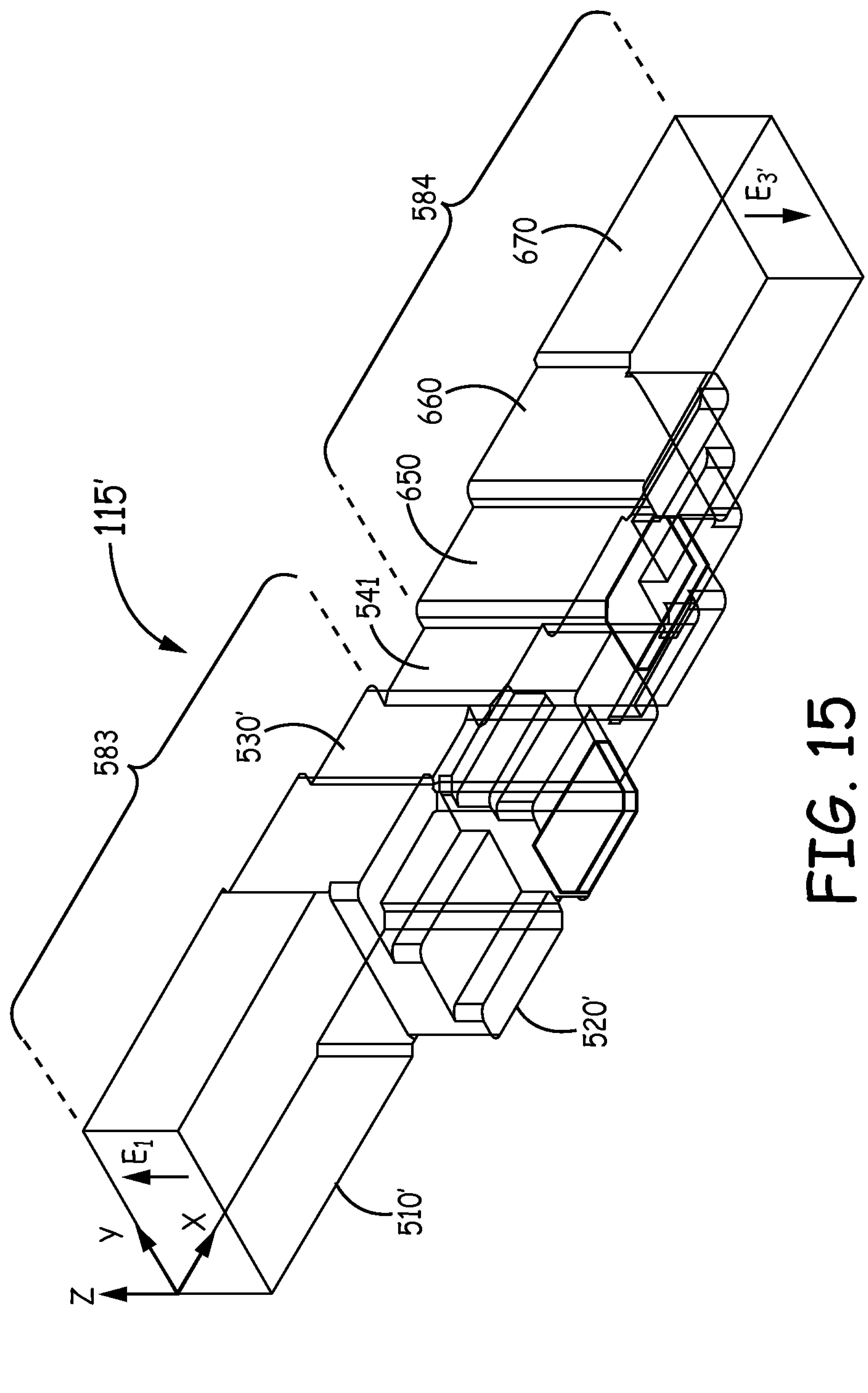


FIG. 15

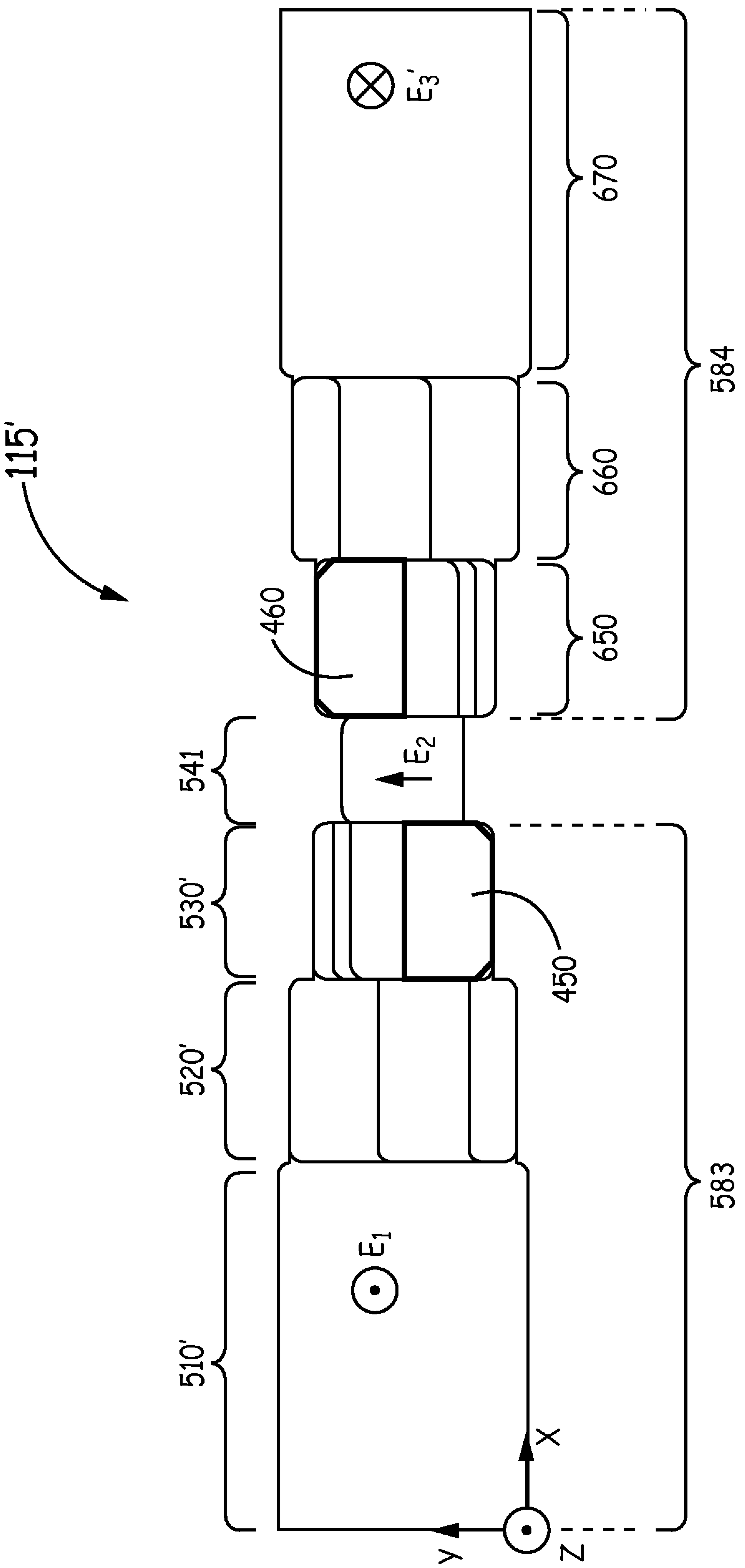


FIG. 16

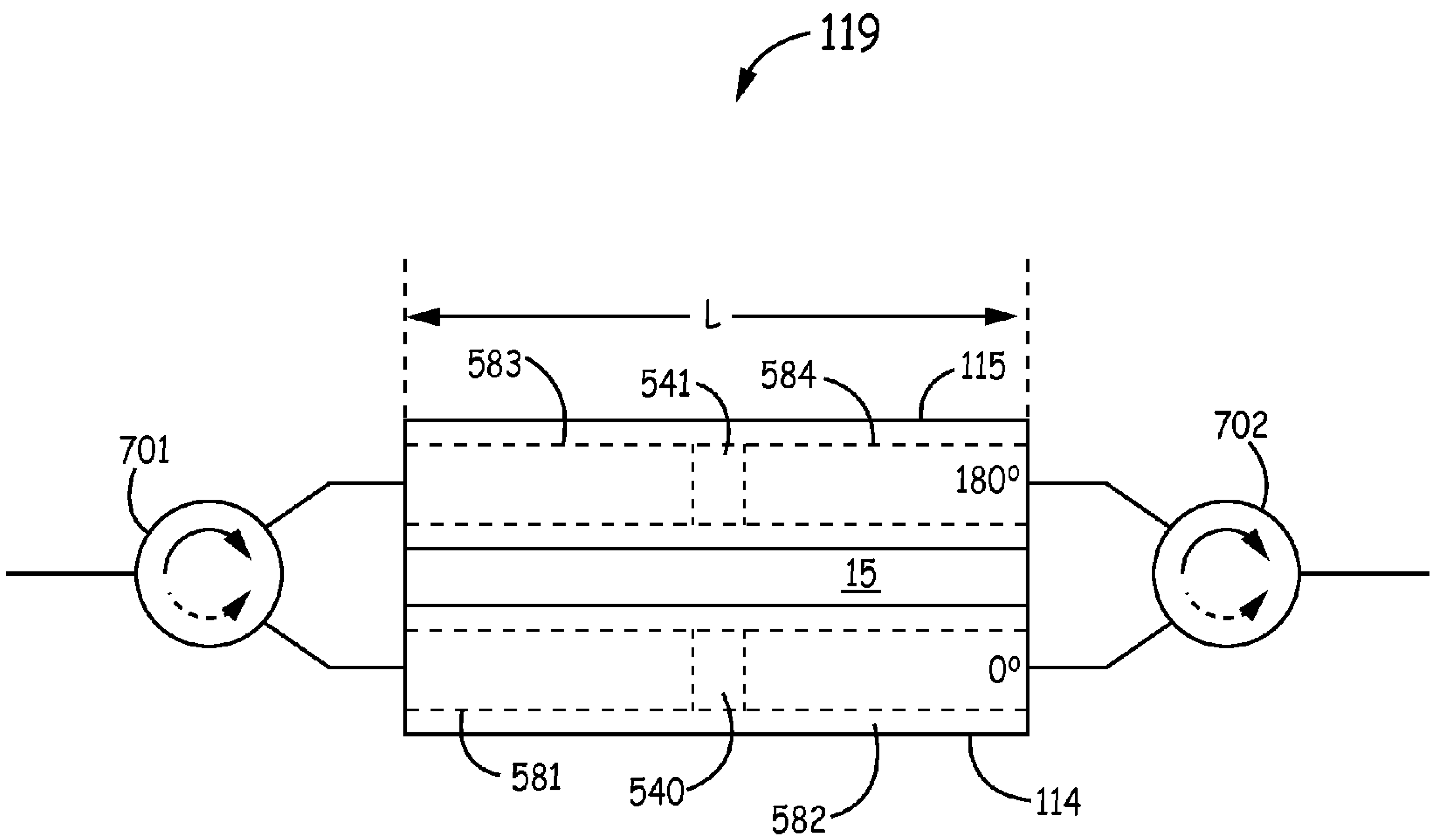


FIG. 17

TWIST FOR CONNECTING ORTHOGONAL WAVEGUIDES IN A SINGLE HOUSING STRUCTURE

BACKGROUND

In the packaging of a waveguide system it is sometimes necessary to change the axial orientation of the waveguide by 90 degrees along the length of a waveguide run. For example, the axial orientation of the waveguide may be required to change from an H-plane orientation to an E-plane orientation or the other way around. For a linearly-polarized antenna, an E-plane is the plane containing the electric field vector in the direction of maximum radiation. An H-plane is the plane containing the magnetic field vector in the direction of maximum radiation. The magnetizing field or H-plane is orthogonal to the E-plane.

The electric field or E-plane determines the polarization and orientation of the radio wave. For a vertically-polarized antenna, the E-plane usually coincides with the vertical/elevation plane and the H-plane coincides with the horizontal/azimuth plane. For a horizontally-polarized antenna, the E-plane usually coincides with the horizontal/azimuth plane and the H-plane coincides with the vertical/elevation plane.

Conventionally, a twist or rotation of the E-field is achieved with an additional curved waveguide section that physically forces the rotation of the orientation of the E-field (and H-field) by 90 degrees as the electro-magnetic (EM) radiation propagates along the length of the curved waveguide. A waveguide that physically forces the rotation of the E-field orientation requires a relatively long waveguide length. Some shorter length twists are currently available. In one example, an additional waveguide section consisting of two quarter wavelength sections orientated at 30 and 60 degrees is placed between the orthogonal waveguides.

Some systems, such as a tightly integrated ferrite switch feed network for an antenna array, require the rotation of an electro-magnetic field from an H-plane orientation to an E-plane orientation to occur within an integrated housing structure, such as a machined aluminum structure. To incorporate such a twist, these assemblies include a feed network that is split into separate E-plane parts, twist parts, and H-plane parts. Thick flanges are required to attach these separate E-plane, twist, and H-plane parts to each other. The positions of the bolts used to attach the various parts must be carefully chosen to ensure the bolt does not protrude into the region of the twisting waveguide.

SUMMARY

The present application relates to a twist for coupling electro-magnetic radiation between orthogonal waveguides. The twist includes at least three cavities having at least three respective shapes, the at least three cavities opening from at least one of a first X1-Y1 surface of a metal block and an opposing second X2-Y2 surface of the metal block. The at least three cavities include a first cavity, a second cavity, and a last cavity. The first cavity has a first opening in a first Y-Z plane and a second opening in a second Y-Z plane that is offset from the first Y-Z plane by a first length along an X axis. The second cavity shares the second opening in the second Y-Z plane with the first cavity and has a third opening in a third Y-Z plane that is offset from the second Y-Z plane by a second length along the X axis. The second cavity has at least two heights and at least two widths. The last cavity shares a next-to-last opening in a next-to-last Y-Z plane with a next-to-last cavity. The last cavity has a last opening in a last Y-Z plane that is offset from the next-to-last Y-Z plane by a last length along the X axis. The orthogonal waveguides are formed from the first cavity and the last cavity.

The details of various embodiments of the claimed invention are set forth in the accompanying drawings and the description below. Other features and advantages will become apparent from the description, the drawings, and the claims.

DRAWINGS

FIG. **1** is a side cross-sectional view of one embodiment of a twist in accordance with the teachings of the present application;

FIG. **2** is a top cross-sectional view of the twist of FIG. **1**;

FIGS. **3** and **4** are oblique views of one embodiment of cavities for a twist formed in a metal block in accordance with the teachings of the present application;

FIG. **5** is an oblique view of one embodiment of cavities in a twist in accordance with the teachings of the present application;

FIG. **6** is an end view of the cavities in the twist of FIG. **5**;

FIG. **7** is a side view of the cavities in the twist of FIG. **5**;

FIG. **8** is a side cross-sectional view of the twist with the cavities of FIG. **5**;

FIG. **9** is an oblique view of one embodiment of cavities in a twist in accordance with the teachings of the present application;

FIG. **10** is an end view of the cavities in the twist of FIG. **9**;

FIG. **11** is an side cross-sectional view of the twist with the cavities of FIGS. **9** and **10**;

FIG. **12** is a flow diagram of one embodiment of a method to form a twist for coupling electro-magnetic radiation between orthogonal waveguides in accordance with the teachings of the present application;

FIG. **13** is an oblique view of one embodiment of cavities in a first-waveguide run for a switch line phase shifter in accordance with the teachings of the present application;

FIG. **14** is a top view of the cavities in the first-waveguide run of FIG. **13** for the switch line phase shifter;

FIG. **15** is an oblique view of one embodiment of cavities in a second-waveguide run for a switch line phase shifter in accordance with the teachings of the present application;

FIG. **16** is a top view of the cavities in the second-waveguide run of FIG. **15** for the switch line phase shifter;

FIG. **17** is a block diagram of a switch line phase shifter including the first-waveguide run of FIGS. **13** and **14** and the second-waveguide run of FIGS. **15** and **16**.

Like reference numbers and designations in the various drawings indicate like elements.

DETAILED DESCRIPTION

The above referenced problems are overcome by a twist formed from a single flange-less housing structure for connecting orthogonal waveguides between which electro-magnetic fields can be coupled over a relatively short straight length. The present application relates to a compact interfacing device for rotating electro-magnetic fields between an input waveguide and an orthogonal output waveguide. The interfacing device includes at least one interfacing cavity that is machined, along with and between an input cavity and an output cavity, from a single metal block. With the attachment of a metal cover over the machined surface, the interfacing cavity, the input cavity, and the output cavity become an interfacing waveguide, an input waveguide, and an output waveguide, respectively. The input waveguide is orthogonal to the output waveguide. Embodiments of the twists described herein include at least one metal cover that caps the input cavity and output cavity and one or more intermediate cavity formed from the single metal block. The twists described herein couple the electro-magnetic radiation between the orthogonal waveguides via the one or more intermediate waveguides. In one implementation of this embodiment, the electro-magnetic radiation is in the radio frequency (RF) spectral range. In another implementation of this embodiment, the electro-magnetic radiation is in the microwave frequency spectral range.

Specifically, the one or more intermediate waveguides rotate by 90 degrees the E-field of electro-magnetic radiation propagating from an input waveguide (also referred to herein as a first waveguide) to an output waveguide (also referred to herein as a last waveguide). The lengths of the intermediate waveguides are about a quarter-wavelength (λ/4) of the wavelength λ, of the radiation propagating in the twist. The adjacent machined cavities are open to each other by shared openings. The first waveguide and the last waveguide have respective openings on opposing outer surfaces of the single housing structure and do not require any flanges for attaching bolts.

In one implementation of this embodiment, the twists described herein are formed by machining the cavities for orthogonal waveguides and the one or more intermediate waveguides from a surface of a single metal block and then attaching a metal cover to the machined surface. In another implementation of this embodiment, the twists described herein are formed by machining the cavities for the orthogonal waveguides and the one or more intermediate waveguides from two opposing surfaces of a single metal block and then attaching two metal covers to the two opposing machined surfaces.

The single housing structure is constructed by machining the cavities from a metal block using standard equipment, such as an end mill in a milling machine or any other available equipment to form cavities in a metal surface.

FIG. **1** is a side cross-sectional view of one embodiment of a twist **5** in accordance with the teachings of the present application. FIG. **2** is a top cross-sectional view of the twist **5** of FIG. **1**. The plane upon which the cross-section view of FIG. **1** is taken is indicated by section line **1-1** in FIG. **2**. The milling tool radius is not shown in FIGS. **1** and **2**. As the electro-magnetic radiation propagates from the first waveguide **56** to the last waveguide **86** in the twist **5**, the electric field vector E_1, which is parallel to the Z axis in the first waveguide **56**, is rotated by 90 degrees to be parallel to the Y axis in the last waveguide **86** as indicated by the electric field vector E_2.

The twist **5** includes three cavities **50**, **60**, and **80** having three respective shapes that are formed in a metal block **15**, and a cover **16**. The metal cover **16** is a flat metal plate. As shown in FIG. **1**, the three cavities **50**, **60**, and **80** open from a surface spanned by an X_1 axis and a Y_1 axis of a metal block **15**. The surface spanned by the X_1 axis and the Y_1 axis is also referred to herein as a "X_1-Y_1 surface" and "a first X_1-Y_1 surface". In one implementation of this embodiment, the three cavities **50**, **60**, and **80** are opened from a surface spanned by an X_1 axis and a Y_1 axis by machining the cavities into the X_1-Y_1 surface. In another implementation of this embodiment, the three cavities **50**, **60**, and **80** are opened from a surface spanned by an X_1 axis and a Y_1 axis by laser drilling into the X_1-Y_1 surface. In yet another implementation of this embodiment, a plastic piece with the desired cavity shapes is formed and coated with metal.

The first cavity **50** has a first opening **51** in a first Y_1-Z_1 plane and a second opening represented generally at **52** in a second Y_2-Z_2 plane. The second Y_2-Z_2 plane is offset from the first Y_1-Z_1 plane by a first length L_1 (FIG. **1**) along the X axis. The first cavity **50** has a width W_1 (FIG. **2**) and a length L_1 (FIG. **1**). The widths described herein are measured parallel to the Y axis. The lengths described herein are measured parallel to the X axis. The heights described herein are measured parallel to the Z axis.

A second cavity **60** shares the second opening **52** in the second Y_2-Z_2 plane with the first cavity **50**. The second cavity **60** has a third opening represented generally at **53** in a third Y_3-Z_3 plane that is offset from the second Y_2-Z_2 plane by a second length L_2 (FIG. **1**) along the X axis. The second length L_2 is about a quarter wavelength (λ/4) of the electro-magnetic radiation propagating through the twist **5** from the first opening **51** to the last opening **54**. The second cavity **60** has two heights H_2 and H_3 (FIG. **1**) and two widths W_2 and W_3 (FIG. **2**) that are the result of a step formed in the second cavity **60**. The rise of the step formed in the second cavity **60** is in an X-Z plane. The tread of the step formed in the second cavity **60** is in an X-Y plane. The second cavity **60** concurrently steps the height and width of the waveguide **66** formed from the second cavity **60** (when the metal cover **16** is attached) to provide the 90° twist effect.

A last cavity **80** shares a next-to-last opening **53** in a next-to-last Y-Z plane Y_3-Z_3 with a next-to-last cavity **60**. In the embodiment shown in FIGS. **1** and **2**, the next-to-last opening **53** in the next-to-last Y_3-Z_3 plane are the third opening **53** in the third Y_3-Z_3 plane and the next-to-last cavity **60** is the second cavity **60**. The last cavity **80** has a last opening **54** in a last Y_4-Z_4 plane that is offset from the next-to-last Y-Z plane by a last length L_{last} along the X axis. When the metal cover **16** (FIG. **1**) is attached to the X_1-Y_1 surface, the orthogonal waveguides **56** and **86** of the twist **5** are formed from the first cavity **50** and the last cavity **80**, respectively.

As shown in FIGS. **1** and **2**, the height H_1 along a Z axis of the first cavity **50** is less than a height H_{last} along a Z axis of the last cavity **80**, a width W_1 along a Y axis of the first cavity **60** is greater than a width W_{last} along a Y axis of the last cavity **80**. In one implementation of this embodiment, the height H_1 along the Z axis of the first cavity **50** is about equal to the width W_{last} along the Y axis of the last cavity **80** and the height H_{last} along the Z axis of the last cavity **80** is about equal to the width W_1 along the Y axis of the first cavity **50**.

As shown in FIG. **1**, the cover **16** is attached to the X_1-Y_1 surface of the metal block **15**, in which the cavities **50**, **60**, and **80** are formed, so the cavities **50**, **60**, and **80** form respective waveguides **56**, **66**, and **86**. In this manner, when the metal cover **16** is attached to the X_1-Y_1 surface, the twist **5** is able to couple electro-magnetic radiation between the orthogonal waveguides **56** and **86** formed from the first cavity **50** and the last cavity **80**. Specifically, when the metal cover **16** is attached to the first X_1-Y_1 surface, the first waveguide **56** is either an input waveguide or an output waveguide, while the last waveguide **86** is a respective one of the output waveguide or the input waveguide depending on the direction of propagation of the electro-magnetic radiation. The metal cover **16** is attached to the first X_1-Y_1 surface by one of a variety of ways including, but not limited to, adhesives, welding, solder, screws, and/or other fixtures.

The first opening **51** in the first Y_1-Z_1 plane is either the input to the input waveguide **56** or an output from the output waveguide **56** depending on the direction of propagation of the electro-magnetic radiation. The last opening **54** in the last Y_4-Z_4 plane is either the output from the output waveguide **86** or an input to the input waveguide **86** depending on the direction of propagation of the electro-magnetic radiation. When the metal cover **16** is attached to the X_1-Y_1 surface, the twist **5** is formed in a single housing structure without the need to attach a separate, bulky, curved prior art waveguide to the input and output waveguides with bolts connecting flanges on the waveguides.

In one implementation of this embodiment, the metal block **15** is made from aluminum and the metal cover **16** is made from aluminum. The metal block **15** and the metal cover **16** can be made from other metal materials.

FIGS. **3** and **4** are oblique views of one embodiment of cavities **310**, **320**, **330**, and **340** for a twist **6** formed in a metal block **15** in accordance with the teachings of the present application. When a metal cover (such as the metal cover **16** shown in FIG. **1**) is attached to the X_1-Y_1 surface of the metal block **15**, the resultant twist **6** couples electro-magnetic radiation between the orthogonal waveguides formed from the first cavity **310** and the last cavity **340**. The interfacing device shown in FIGS. **3** and **4** consists of the two cavities **320** and **330** that are each approximately a quarter wavelength (λ/4) in length. The four cavities **310**, **320**, **330**, and **340** have four respective shapes. The four cavities **310**, **320**, **330**, and **340** are manufactured by milling all of the openings from the X1-Y1 plane. The milling tool radius is shown in FIGS. **3** and **4**.

The first cavity **310** has a first opening **51** in the Y_1-Z_1 plane. The first opening **51** functions as an input port or output port of the waveguide formed from the first cavity **310** when the metal cover **16** is attached. The first cavity **310** has a second opening in a second Y_2-Z_2 plane offset from the Y_1-Z_1 plane by the length L_1 along the X axis.

The second cavity **320** has three heights (not labeled) and three widths W_{2-1}, W_{2-2}, and W_{2-3} that are the result of two steps formed in the second cavity **320**. The rises of the two steps formed in the second cavity **320** are in X-Z planes. The treads of the two steps formed in the second cavity **320** are in X-Y planes. The second cavity **320** shares the opening in the second Y-Z plane with the first cavity **310**. The second cavity **320** has a third opening in a third Y-Z plane offset from the second Y-Z plane by a second length L_2 along the X axis. The second length L_2 is approximately a quarter wavelength (λ/4) in length. The three heights in the second cavity **320** are referred to herein as three second-cavity heights. The three widths in the second cavity **320** are referred to herein as three second-cavity heights.

The third cavity **330** has four heights (not labeled) and four widths W_{3-1}, W_{3-2}, W_{3-3}, and W_{3-4} that are the result of three steps formed in the third cavity **330**. The rises of the three steps formed in the third cavity **330** are in X-Z planes. The treads of the three steps formed in the third cavity **330** are in X-Y planes. The third cavity **330** shares the opening in the third Y-Z plane with the second cavity **320**. The third cavity **330** has a fourth opening in a fourth Y-Z plane offset from the third Y-Z plane by a third length L_3 (FIG. **3**) along the X axis. The third length L_3 is approximately a quarter wavelength (λ/4) in length. The four heights in the third cavity **330** are referred to herein as four third-cavity heights. The four widths in the third cavity **330** are referred to herein as four third-cavity heights. As shown in FIG. **4**, $W_{3-1}<W_{3-2}<W_{3-3}<W_{3-4}$. The third cavity **330** is referred to herein as a next-to-last cavity **330**. The fourth Y-Z plane referred to herein as a next-to-last Y-Z plane.

A dielectric material **450** is shown positioned in the floor of the third cavity **330**. In one implementation of this embodiment, the dielectric material **450** is bonded to the floor of the third cavity **330**. In one implementation of this embodiment, the dielectric material **450** has a dielectric constant of 4 or higher. In another implementation of this embodiment, the dielectric material **450** is formed from Corderite or Boron Nitride. The dielectric material **450** inserted in the third cavity **330** improves the bandwidth of the electro-magnetic radiation that can be rotated while propagating between the first waveguide formed from the first cavity **310** and the fourth waveguide formed from the fourth cavity **340**.

The fourth cavity **340** is referred to herein as a last cavity **340**. The last cavity **340** shares the next-to-last opening in the next-to-last Y-Z plane with the next-to-last cavity **330**. The last cavity **340** has a last opening (fifth opening) in the last Y-Z plane (fifth Y-Z plane). The fifth Y-Z plane is offset from the fourth Y-Z plane by a fourth length L_4 along the X axis (FIG. **3**). The fifth opening in the Y_5-Z_5 plane of the fourth cavity **340** is an input port or output port of the waveguide formed from the fourth cavity **340** when a metal cover is attached to the metal block **15**.

The four cavities **310**, **320**, **330**, and **340** concurrently step the height and width of the waveguide to provide the 90° twist effect. The interfacing device **320/330** formed from the two cavities **320** and **330** shown in FIGS. **3** and **4** provides a broader operating bandwidth than the single cavity interfacing device **60** shown in FIGS. **1** and **2**. In another implementation of this embodiment, the interfacing device includes three cavities with steps positioned between the first and last cavities. As the number of interfacing cavities increases the operational bandwidth of the twist increases.

FIG. **5** is an oblique view of one embodiment of cavities **150**, **160**, **170**, and **180** in a twist **7'** in accordance with the teachings of the present application. FIG. **6** is an end view of the cavities **150**, **160**, **170**, and **180** in the twist **7'** of FIG. **5**. FIG. **7** is a side view of the cavities **150**, **160**, **170**, and **180** in the twist **7'** of FIG. **5**. FIG. **8** is a side cross-sectional view of the twist **7** with the cavities of FIG. **5**. As defined herein, the twist **7'** includes the outlines of the cavities **150**, **160**, **170**, and **180** in the twist **7** (FIG. **8**) without the surrounding metal in order to clearly indicate the shapes of the cavities that are formed in metal shown in the twist **7** of FIG. **8**. The four cavities **150**, **160**, **170**, and **180** have four respective shapes. The cavities **150**, **160**, **170**, and **180** represented generally as twist **7'** are shown without the metal cover **16** in the twist **7** shown in FIG. **8**. When the cover **16** is attached to the metal block **15** with the cavities **150**, **160**, **170**, and **180**, the cavities **150**, **160**, **170**, and **180** form respective waveguides **156**, **166**, **176**, and **186**. As the electro-magnetic radiation propagates from the first waveguide **156** to the last waveguide **186** in the twist **7** (FIG. **8**), the electric field vector E_1, which is parallel to the Z axis (e.g., perpendicular to the broad wall of the first waveguide **156**) is rotated by 90 degrees to be output from the last waveguide **186** as the electric field vector E_2, which is parallel to the Y axis (e.g., perpendicular to the broad wall of the last waveguide **186**)

The twist **7** is similar to the twist **6** of FIGS. **3** and **4** in that the interfacing device **160/170** includes two cavities **160** and **170** that interface with the first cavity **150** and the last cavity **180**. The twist **7** does not include the dielectric material of twist **6**. The interfacing device **160/170** shown in FIGS. **5-8** consists of 2 sections of approximately a quarter wavelength (λ/4) in length. These four cavities **150**, **160**, **170**, and **180** concurrently step the height and width of the waveguide to provide the 90° twist effect, and they can be manufactured by milling all of the openings from X_1-Y_1 surface of the metal block **15** (FIG. **8**). The milling tool radius is not shown in FIGS. **5-8**.

When the metal cover **16** (FIG. **8**) is attached to the X_1-Y_1 surface of the metal block **15** (FIG. **8**), the resultant twist **7** couples electro-magnetic radiation between the orthogonal waveguides **156** and **186** (FIG. **8**) formed from the first cavity **150** and the last cavity **180**.

The first cavity **150** has a first opening **151** (FIGS. **5** and **7**) (that is an input port or output port of the waveguide formed from the first cavity **150** when the metal cover is attached) in the Y_1-Z_1 plane and a second opening **152** (FIGS. **5** and **7**) in a second Y_2-Z_2 plane offset from the Y_1-Z_1 plane by the length L_1 along the X axis.

The second cavity **160** has three heights H_{2-3}, H_{2-2}, H_2 (FIG. **6**) and three widths (not labeled) that are the result of two steps formed in the second cavity **160**. The rises of the two steps formed in the second cavity **160** are in X-Z planes. The treads of the two steps formed in the second cavity **160** are in X-Y planes. The second cavity **160** shares the second opening **152** (FIGS. **5** and **7**) in the second Y-Z plane with the first cavity **150**. The second cavity **160** has a third opening **153** (FIGS. **5** and **7**) in a third Y-Z plane offset from the second Y-Z plane by a second length L_2 along the X axis. The second length L_2 is approximately a quarter wavelength (λ/4) in length. The three heights in the second cavity **160** are referred to herein as three second-cavity heights. As shown in FIG. **7**, $H_{2-3}<H_{2-2}<H_2$. The three widths in the second cavity **160** are referred to herein as three second-cavity widths.

The third cavity **170** has three heights H_{3-3}, H_{3-2}, H_3 and three respective widths (not labeled) that are the result of the two steps formed in the third cavity **170**. The rises of the two steps formed in the third cavity **170** are in X-Z planes. The treads of the two steps formed in the third cavity **170** are in X-Y planes. The third cavity **170** shares the third opening **153** (FIGS. **5** and **7**) in the third Y-Z plane with the second cavity **160**. The third cavity **170** has a fourth opening **154** (FIGS. **5** and **7**) in a fourth Y-Z plane offset from the third Y-Z plane by a third length L_3 (FIGS. **5** and **7**) along the X axis. The third length L_3 is approximately a quarter wavelength (λ/4) in length. The three heights in the third cavity **170** are referred to herein as three third-cavity heights. The three widths in the third cavity **170** are referred to herein as three third-cavity widths. As shown in FIG. **7**, $H_{3-3}<H_{3-2}<H_3$. The third cavity **170** is referred to herein as a next-to-last cavity **170**. The fourth Y-Z plane is referred to herein as a next-to-last Y-Z plane.

The fourth cavity **180** is referred to herein as a last cavity **180**. The last cavity **180** shares the next-to-last opening **154** (FIGS. **5** and **7**) in the next-to-last Y-Z plane with the next-to-last cavity **170**. The last cavity **180** has a last opening (fifth opening) **155** (FIGS. **5** and **7**) in the last Y-Z plane (fifth X-Y plane). The fifth Y-Z plane is offset from the fourth Y-Z plane by a fourth length L_4 along the X axis. The fifth opening **155** (FIGS. **5** and **7**) in the Y_5-Z_5 plane of the fourth cavity **180** is an input port or output port of the waveguide **186** (FIG. **8**) formed from the fourth cavity **180** when the metal cover **16** (FIG. **8**) is attached to the metal block **15**.

The interfacing device **160/170** formed from the two waveguides **166** and **176** (FIG. **8**), which include the respective cavities **160** and **170** shown in FIGS. **5-8**, provides a broader operating bandwidth than the single cavity interfacing device shown in FIGS. **1** and **2**.

As shown in FIGS. **5-8**, the height H_1 measured along a Z axis of the first cavity **150** is less than a height H_4 measured along a Z axis of the last cavity **180** (FIG. **7**), a width W_1 (FIG. **5**) along a Y axis of the first cavity **150** is greater than a width W_4 (FIG. **5**) along a Y axis of the last cavity **180**. In one implementation of this embodiment, the height H_1 along the Z axis of the first cavity **150** is about equal to the width W_4 along the Y axis of the last cavity **180** and the height H_4 along the Z axis of the last cavity **180** is about equal to the width W_1 along the Y axis of the first cavity **150**.

FIG. **9** is an oblique view of one embodiment of cavities **410**, **420**, **430**, and **440** in a twist **8'** in accordance with the teachings of the present application. FIG. **10** is an end view of the cavities **410**, **420**, **430**, and **440** in the twist **8'** of FIG. **9**. FIG. **11** is a side cross-sectional view of the twist **8** with the cavities **410**, **420**, **430**, and **440** of FIGS. **9** and **10**. As defined herein, the twist **8'** includes the outlines of the cavities **410**, **420**, **430**, and **440** in the twist **8** (FIG. **11**) without the surrounding metal in order to clearly indicate the shapes of the cavities **410**, **420**, **430**, and **440** that are formed in metal shown in the twist **8** of FIG. **11**. To form the twist **8** shown in FIG. **11**, the metal cover **16** and metal cover **17** are attached to the metal block **15** in which the cavities **410**, **420**, **430**, and **440** are formed. Specifically, when the metal cover **16** and the metal cover **17** are attached to the metal block **15**, the cavities **410**, **420**, **430**, and **440** form respective waveguides **416**, **426**, **436**, and **446**. The metal cover **16** is a flat sheet of metal. As shown in FIG. **11**, the metal plate **17** includes a protrusion **18** that extends from a flat surface **19** of the metal cover **17**. The protrusion **18** forms a surface of the waveguide **426** in the twist **8** (FIG. **11**). The flat surface **19** of the metal cover **17** forms a surface of the waveguide **436** in the twist **8** (FIG. **11**). When the metal cover **16** is attached to the first X_1-Y_1 surface and the metal cover **17** is attached to the second X_2-Y_2 surface, the twist **8** is formed in a single housing structure without the need to attach a separate, bulky, curved waveguide to the input and output waveguides with bolts. The metal cover **17** is attached to the second X_2-Y_2 surface by one of a variety of ways including, but not limited to, adhesives, solder, screws, and/or other fixtures.

As indicated, the cavities **410**, **420**, **430**, and **440** in the metal block **15** represented generally as twist **8'** are the portion of the twist **8** shown in FIG. **11** without the covers **16** and **17** shown in FIG. **11**. The four cavities **410**, **420**, **430**, and **440** have four respective shapes. The twist **8** is similar to the twist **7** of FIG. **8** in that the interfacing device **420/430** includes two cavities **420** and **430** that interface with the first cavity **410** and the last cavity **440**. The two cavities **420** and **430** that form the interfacing device **420/430** shown in FIGS. **9-11** are approximately a quarter wavelength (λ/4) in length.

The twist **8** as shown does not include dielectric material; however dielectric material may be positioned in one or both of the waveguides **426** and **436**.

The twist **8** is manufactured by milling cavities from two opposing surfaces of the metal block **15**. The twist **8** is manufactured by milling cavities **410** and **440** and portions of cavities **420** and **430** from the surface of the metal block **15** spanned by the X_1 axis and the Y_1 axis (e.g., the first X_1-Y_1 surface) and by milling portions of the cavities **420** and **430** from the surface of the metal block **15** spanned by the X_2 axis and the Y_2 axis (FIG. **11**). The surface spanned by the X_2 axis and the Y_2 axis is also referred to herein as an "X_2-Y_2 surface" and "a second X_2-Y_2 surface". The milling tool radius is not shown in FIGS. **9-11**.

When the metal covers **16** and **17** (FIG. **11**) are attached to the respective X_1-Y_1 surface and X_2-Y_2 surface of the metal block **15** (FIG. **11**), the resultant twist **8** couples electro-magnetic radiation between the orthogonal waveguides **416** and **446** (FIG. **11**) formed from the first cavity **410** and the last cavity **440**. As the electro-magnetic radiation propagates from the first waveguide **416** to the last waveguide **446** in the twist **8**, the electric field vector E_1, which is parallel to the Z axis in the first waveguide **416**, is rotated by 90 degrees to be parallel to the Y axis in the last waveguide **446** as indicated by the electric field vector E_2.

The height H_1 along a Z axis of the first cavity **410** is less than a height H_4 along a Z axis of the last cavity **440** (FIG. **10**), a width W_1 along a Y axis of the first cavity **410** is greater than a width W_4 along a Y axis of the last cavity **440** (FIG. **9**). In one implementation of this embodiment, the height H_1 along the Z axis of the first cavity **410** is about equal to the width W_4 along the Y axis of the last cavity **440** and the height H_4 along the Z axis of the last cavity **440** is about equal to the width W_1 along the Y axis of the first cavity **410**.

The first cavity **410** has a first opening **151** (FIG. **11**), which is an input port or output port of the waveguide **416** formed from the first cavity **410** when the metal cover **16** is attached to the X_1-Y_1 surface. A second opening **152** (FIG. **11**) in a second Y-Z plane offset from the Y_1-Z_1 plane by the length L_1 along the X axis.

The second cavity **420** has three heights (not labeled) and three widths (not labeled) that are the result of two steps formed in the second cavity **420**. The rises of the two steps formed in the second cavity **420** are in X-Z planes. The treads of the two steps formed in the second cavity **420** are in X-Y planes. The second cavity **420** shares the second opening **152** (FIG. **11**) in the second Y-Z plane with the first cavity **410**. The second cavity **420** has a third opening **153** (FIG. **11**) in a third Y-Z plane offset from the second Y-Z plane by a second length L_2 along the X axis. The second length L_2 is approximately a quarter wavelength ($\lambda/4$) in length. The three heights in the second cavity **420** are referred to herein as three second-cavity heights. The three widths in the second cavity **420** are referred to herein as three second-cavity heights.

The third cavity **430** has three heights (not labeled) and four widths (not labeled) that are the result of the two steps formed in the third cavity **430**. The rises of the two steps formed in the third cavity **430** are in X-Z planes. The treads of the two steps formed in the third cavity **430** are in X-Y planes. The third cavity **430** shares the third opening **153** (FIG. **11**) in the third Y-Z plane with the second cavity **420**. The third cavity **430** has a fourth opening **154** (FIG. **11**) in a fourth Y-Z plane offset from the third Y-Z plane by a third length L_3 (FIG. **11**) along the X axis. The third length L_3 is approximately a quarter wavelength ($\lambda/4$) in length. The three heights in the third cavity **430** are referred to herein as three third-cavity heights. The three widths in the third cavity **430** are referred to herein as three third-cavity heights. The third cavity **430** is referred to herein as a next-to-last cavity **430**. The fourth Y-Z plane referred to herein as a next-to-last Y-Z plane.

The fourth cavity **440** is referred to herein as a last cavity **440**. The last cavity **440** shares the next-to-last opening **154** (FIG. **11**) in the next-to-last Y-Z plane with the next-to-last cavity **430**. The last cavity **440** has a last opening (fifth opening) **155** (FIG. **11**) in the last Y-Z plane (fifth X-Y plane). The fifth Y-Z plane is offset from the fourth Y-Z plane by a fourth length L_4 along the X axis. The fifth opening **155** (FIG. **11**) in the Y_5-Z_5 plane of the fourth cavity **440** is an input port or output port of the waveguide **446** formed from the fourth cavity **440** when the metal cover is attached to the X_1-Y_1 surface.

The four cavities **410**, **420**, **430**, and **440** concurrently step the height and width of the waveguide to provide the 90° twist effect. The interfacing device **420**/**430** formed from the two waveguides **426** and **436** (FIG. **11**), which include the respective cavities **420** and **430** shown in FIGS. **9**-**11**, provides a broader operating bandwidth than the single cavity interfacing device **60** shown in FIGS. **1** and **2**. Although the illustrated embodiments include 1 or 2 quarter-wave transition cavities more than two quarter-wave transition cavities can be designed and fabricated for a broader operating bandwidth. The bandwidth and size of the structure will both improve as more sections are added as is known in the art.

FIG. **12** is a flow diagram of one embodiment of a method **1200** to form a twist for coupling electro-magnetic radiation between orthogonal waveguides in accordance with the teachings of the present application. The method **1200** is used to form any of the twists **5**, **6**, **7**, and **8** described herein.

At block **1202**, a first cavity having a first shape is formed in a first X_1-Y_1 surface of a metal block. The first cavity has a first opening in a first Y-Z plane and a second opening in a second Y-Z plane. The second Y-Z plane is offset from the first Y-Z plane by a first length L_1 along an X axis.

At block **1204**, a second cavity having a second shape is formed in at least one of the first X_1-Y_1 surface of the metal block and an opposing second X_2-Y_2 surface of the metal block. The twist **8** shown in FIG. **11** requires second cavity **420** to be formed in both the first X_1-Y_1 surface of the metal block **15** and the opposing second X_2-Y_2 surface of the metal block **15**.

The second cavity shares the second opening in the second Y-Z plane with the first cavity. The second cavity has a third opening in a third Y-Z plane that is offset from the second Y-Z plane by a second length along the X axis. The second cavity has at least two heights and at least two widths. The at least two heights and at least two widths are associated with each other and are due to at least one step in the second cavity.

In one implementation of this embodiment, the second cavity is formed with two second-cavity heights along the Z axis and the second cavity is formed with two second-cavity widths along a Y axis. In another implementation of this embodiment, the second cavity is formed with three second-cavity heights along the Z axis and the second cavity is formed with three second-cavity widths along a Y axis. In yet another implementation of this embodiment, the second cavity is formed with more than three second-cavity heights along the Z axis and the second cavity is formed with more than three second-cavity widths along a Y axis. In yet another implementation of this embodiment, a dielectric material is positioned in the second cavity.

Block **1206** is optional. The twist **5** shown in FIG. **1** is formed without implementing block **1206**. At block **1206**, a third cavity having a third shape is formed in at least one of the first X_1-Y_1 surface and the opposing second X_2-Y_2 surface. The twist **8** shown in FIG. **11** requires third cavity **430** to be formed in both the first X_1-Y_1 surface of the metal block **15** and the opposing second X_2-Y_2 surface of the metal block **15**.

The third cavity shares the third opening in the third Y-Z plane with the second cavity. The third cavity has a fourth opening in a fourth Y-Z plane that is offset from the third Y-Z plane by a third length along the X axis. The third cavity has at least two heights and at least two widths. The at least two heights and at least two widths are associated with each other and are due to at least one step in the third cavity.

In one implementation of this embodiment, the third cavity is formed with two third-cavity heights along the Z axis and the third cavity is formed with two third-cavity widths along a Y axis. In another implementation of this embodiment, the third cavity is formed with three third-cavity heights along the Z axis and the third cavity is formed with three third-cavity widths along a Y axis. In yet another implementation of this embodiment, the third cavity is formed with more than three third-cavity heights along the Z axis and the third cavity is formed with more than three third-cavity widths along a Y axis. In yet another implementation of this embodiment, a dielectric material is positioned in the third cavity.

At block **1208**, a last cavity having a last shape is formed in at least one of the first X_1-Y_1 surface of the metal block and the opposing second X_2-Y_2 surface of the metal block. The last cavity has a last opening in a last Y-Z plane that is offset from a next-to-last Y-Z plane by a last length. As described above, in some embodiments, the last cavity is a fourth cavity or a third cavity. In one implementation of this embodiment, a first height along a Z axis of the first cavity is formed to be approximately equal to a last width of the last cavity along a Y axis of the last cavity. In another implementation of this embodiment, a last height along a Z axis of the last cavity is formed to be approximately equal to a first width of the first cavity along a Y axis of the first cavity. In yet another implementation of this embodiment, there are more than four cavities formed in the metal block.

The shapes of the cavities formed in blocks **1202**, **1204**, **1206**, and **1208** are designed using commercial 3D electromagnetic design software. The designer adds one or more quarter-wave waveguide interfacing sections (e.g., such as the second and third cavities formed in blocks **1204** and **1206**) that are aligned between an E-plane and an H-plane waveguide section (e.g., such as the first and last cavities formed in blocks **1202** and **1208**). Each quarter-wave section is constructed of several diagonally aligned subsections formed from one or more steps formed in the one or more quarter-wave waveguide interfacing sections. The angle between the sections is selected to be closer to that of an E-plane orientation closer to the E-plane waveguide and closer to an H-plane orientation for the sections closer to the H-plane waveguide. Once the basic design is determined, the designer optimizes the size, length, and orientation of the subsections formed by the steps in each interfacing section to meet the return loss goal over a desired bandwidth. Typically, a quarter-wavelength is an approximate length to these interfacing sections and the actual length is optimized for performance. The designer ensures that the dimensions of the individual sections are large enough so that an end mill of a diameter, such as 1⁄32, can pass through the sections from a single side.

If the desired performance is not met at this point, the designer has various additional options to enhance the performance can be implemented. These additional options include, but are not limited to: 1) add waveguide features manufactured from a second side (e.g., the second X_2-Y_2 plane), which is opposite from the first side (e.g., the first X_1-Y_1 plane); 2) add additional matching sections (e.g., add a additional interfacing quarter-wave waveguide section between the first and last cavities formed in blocks **1202** and **1208**; 3) add dielectric segments with the size, dielectric constant, and position optimized using the standard design software. The optimization process is repeated after each additional feature is added or modified.

At block **1210**, a first metal cover is attached to the first X_1-Y_1 surface of the metal block from which the cavities are formed. Block **1212** is optional and is only implemented if at least one cavity is machined from the second X_2-Y_2 surface of the metal block. At block **1212**, a second metal cover is attached to the second X_2-Y_2 surface of the metal block from which the cavities at least a portion of the cavities are formed. In this manner, the cavities are functional as waveguides to electro-magnetic radiation.

Broadband phase offset lines are able to be made in like manner for use in a switched line phase shifter. Advantageously, the technology described herein can be used to form two waveguide runs in a single metal block (or in two adjacently positioned metal blocks) in which the waveguide runs of the same physical length are formed. In one implementation of this embodiment, the two waveguide runs are designed to output two electro-magnetic radiation signals that are polarized parallel to each and that are 180° out of phase with respect to each other. In another implementation of this embodiment, the two waveguide runs are connected to an input ferrite switching circulator and an output ferrite switching circulator in a single mechanical housing assembly (metal block) to form a switched line phase shifter.

FIG. **13** is an oblique view of one embodiment of cavities **510**, **520**, **530**, **540**, **550**, **560**, and **570** in a first-waveguide run **114'** for a switch line phase shifter **119** (FIG. **17**) in accordance with the teachings of the present application. FIG. **14** is a top view of the cavities **510**, **520**, **530**, **540**, **550**, **560**, and **570** in the first-waveguide run **114'** of FIG. **13** for the switch line phase shifter **119**. FIG. **15** is an oblique view of one embodiment of cavities **510'**, **520'**, **530'**, **541**, **650**, **660**, and **670** in a second-waveguide run **115'** for a switch line phase shifter **119** (FIG. **17**) in accordance with the teachings of the present application. FIG. **16** is a top view of the cavities **510'**, **520'**, **530'**, **541**, **650**, **660**, and **670** in the second-waveguide run **115'** of FIG. **15** for the switch line phase shifter **119** (FIG. **17**). FIG. **17** is a block diagram of a switch line phase shifter **119** including the first-waveguide run **114** of FIGS. **13** and **14** and the second-waveguide run **115** of FIGS. **15** and **16**. As defined herein, the first-waveguide run **114'** (FIGS. **13** and **14**) includes the outlines of the cavities **510**, **520**, **530**, **540**, **550**, **560**, and **570** in the first-waveguide run **114** (FIG. **17**) without the surrounding metal in order to clearly indicate the shapes of the cavities **510**, **520**, **530**, **540**, **550**, **560**, and **570** that are formed in metal shown in the first-waveguide run **114** of FIG. **17**. Likewise, as defined herein, the second-waveguide run **115'** (FIGS. **15** and **16**) includes the outlines of the cavities **510'**, **520'**, **530'**, **541**, **650**, **660**, and **670** in the second-waveguide run **115** (FIG. **17**) without the surrounding metal in order to clearly indicate the shapes of the cavities **510'**, **520'**, **530'**, **541**, **650**, **660**, and **670** that are formed in metal shown in the second-waveguide run **115** of FIG. **17**.

The cavities **510**, **520**, **530**, **540**, **550**, **560**, and **570** in the first-waveguide run **114'** and the cavities **510'**, **520'**, **530'**, **541**, **650**, **660**, and **670** in the second-waveguide run **115'** all open from at least one of a first X_1-Y_1 surface of the metal block **15** and an opposing second X_2-Y_2 surface of the metal block **15**.

When a metal cover or covers (e.g., metal cover **16** and/or metal cover **17** as described above) are attached to the metal block **15** from which the cavities **510**, **520**, **530**, **540**, **550**, **560**, and **570** in the first-waveguide run **114** (FIG. **17**) and the cavities **510'**, **520'**, **530'**, **541**, **650**, **660**, and **670** in the second-waveguide run **115** (FIG. **17**) are formed, the cavities **510**, **520**, **530**, **540**, **550**, **560**, and **570** in the first-waveguide run **114** (FIG. **17**) and the cavities **510'**, **520'**, **530'**, **541**, **650**, **660**, and **670** in the second-waveguide run **115** (FIG. **17**) function as waveguides through which electro-magnetic radiation is able to propagate.

The cavities **510**, **520**, **530**, **550**, **560**, and **570** in the first-waveguide run **114'** and the cavities **510'**, **520'**, **530'**, **650**, **660**, and **670** in the second-waveguide run **115'** are also referred herein to as follows: first cavity **510**; second cavity **520**; third cavity **560**; fourth cavity **570**; fifth cavity **510'**; sixth cavity **520'**; seventh cavity **660**; eighth cavity **670**; ninth cavity **530**; tenth cavity **550**; eleventh cavity **530'**; and twelfth cavity **650**. In one implementation of this embodiment, the first-waveguide run **114'** and the second-waveguide run **115'** do not include the ninth cavity **530**, the tenth cavity **550**, the eleventh cavity **530'**, and the twelfth cavity **650**.

The first-waveguide run **114** (FIG. **17**) includes a first twist **581**, a second twist **582**, and a first connecting cavity **540** (FIG. **17**). The first connecting cavity **540** couples electro-magnetic radiation propagating along an X axis between the first twist **581** and the second twist **582**. The first twist **581** rotates the electro-magnetic radiation by 90 degrees. The second twist **582** rotates the electro-magnetic radiation by 90 degrees in the opposite direction. In this manner, the input radiation represented generally as E_1 in the cavity **510** is the same polarization as the output electro-magnetic radiation represented generally as E_3 in the cavity **570** (FIGS. **13** and **14**). The input radiation E_1 is in-phase with output radiation E_3.

The second-waveguide run **115** includes a third twist **583**, a fourth twist **584**, and a second connecting cavity **541**. The second connecting cavities **540** and **541** have the same shape. The second connecting cavity **541** couples electro-magnetic radiation propagating along an X axis between the third twist **583** and the fourth twist **584**. The third twist **583** rotates the electro-magnetic radiation by 90 degrees. The fourth twist **584** rotates the electro-magnetic radiation by an additional 90 degrees in the same direction. The input radiation E_1 in the cavity **510'** is the same polarization as the output electro-magnetic radiation E_3' in the cavity **670**. The input radiation E_1 is 180 degrees out of phase with the output radiation E_3'. Thus, the output radiation E_3' is 180 degrees out of phase with the output radiation E_3.

The first twist **581** includes the first cavity **510**, the second cavity **520**, and the ninth cavity **530**. The first cavity **510**, the second cavity **520**, and the ninth cavity **530** have three respective shapes. The second twist **582** includes the third cavity **560**, the fourth cavity **570**, and the tenth cavity **550**. The third cavity **560** has the shape of the second cavity **520**. The fourth cavity **570** has the shape of the first cavity **510**. The ninth cavity **530** has the shape of the tenth cavity **550**.

The third twist **583** includes the fifth cavity **510'**, the sixth cavity **520'**, and the eleventh cavity **530'**. The fifth cavity **510'**, the sixth cavity **520'**, and the eleventh cavity **530'** have three respective shapes. The fourth twist **584** includes the seventh cavity **660**, the eighth cavity **670**, and the twelfth cavity **650**. The seventh cavity **660** has the shape of the sixth cavity **520'** rotated 180 degrees about a Z axis. The eleventh cavity **530'** has the shape of the twelfth cavity **650** rotated 180 degrees about a Z axis.

As described above, the electro-magnetic radiation propagating along the X axis from the third twist **583** to the fourth twist **584** is output from the eighth cavity **670** as electro-magnetic radiation E_3' and electro-magnetic radiation propagating along the X axis from the first twist **581** to the second twist **582** that is output from the fourth cavity **570** as electro-magnetic radiation E_3. The electro-magnetic radiation E_3 is polarized parallel to electro-magnetic radiation E_3' and is 180 degrees out of phase with electro-magnetic radiation E_3'. This phase difference between E_3 and E_3' is due to the above described difference in shape between: the third cavity **560** in the first-waveguide run **114** and the seventh cavity **660** in the second-waveguide run **115**; and the tenth cavity **550** in the first-waveguide run **114** and the twelfth cavity **650** the second-waveguide run **115**.

The first-waveguide run **114** includes dielectric material **450** in cavity **530** and dielectric material **460** in cavity **550**. The second-waveguide run **115** includes dielectric material **450** in cavity **530'** and dielectric material **460** in cavity **650**. In one implementation of this embodiment, the first-waveguide run **114** and the second-waveguide run **115** do not include dielectric materials.

The switch line phase shifter **119**, as shown in FIG. **17**, includes the first-waveguide run **114** of FIGS. **13** and **14** and the second-waveguide run **115** of FIGS. **15** and **16**, at least one metal cover (not visible in FIG. **17**) attached to at least the first X_1-Y_1 surface of the metal block **15**, a first switch **701**, and a second switch **702**. The cavities of first-waveguide run **114** and the second-waveguide run **115** are formed from at least one of the first X_1-Y_1 surface of a metal block **15** and an opposing second X_2-Y_2 surface of the metal block **15**.

If any of the cavities **510**, **520**, **530**, **540**, **550**, **560**, **570**, **510'**, **520'**, **530'**, **541**, **650**, **660**, and **670** in the first, second, third, and fourth twists or first and second connecting cavities **540**, and **541** are formed in the second X_2-Y_2 surface of the metal block **15**, then the switch line phase shifter **119** includes a second metal cover (e.g., metal cover **17**).

The first switch **701** is arranged to one of output or input electro-magnetic radiation to or from one of the first twist **581** and the third twist **853**. A second switch **702** is arranged to respectively one of input or output electro-magnetic radiation from or to one of the second twist **852** and the fourth twist **854**.

For a first direction of electromagnetic signal propagation, the first twist **581** and the third twist **583** are arranged to input electro-magnetic radiation from the first switch **701** and the second twist **582** and the fourth twist **584** are arranged to output electro-magnetic radiation to the second switch **702**. If an electro-magnetic signal is input to the first twist **581** from the first switch **701**, the electro-magnetic signal is output from the second twist **582** to the second switch **702**. Likewise, if an electro-magnetic signal is input to the third twist **583** from the first switch **701**, the electro-magnetic signal is output from the fourth twist **584** to the second switch **702**. The electro-magnetic signal propagates through one of the first-waveguide run **114** or the second-waveguide run **115** at any given time. The switch line phase shifter **119** is operable to switch between having the electro-magnetic radiation propagate through the first-waveguide run **114** to having the electro-magnetic radiation propagate through the second-waveguide run **115** and vice versa. Thus, the switch line phase shifter **119** is a compact device milled from a single housing structure configured to provide a switchable phase shift of 180 degrees.

The switch line phase shifter **119** is bidirectional so the electro-magnetic radiation can propagate in the opposite direction. Other configurations are of the switch line phase shifter **119** are possible as is understandable to the one skilled in the art upon reading this document.

EXAMPLE EMBODIMENTS

Example 1 includes a twist for coupling electro-magnetic radiation between orthogonal waveguides, the twist comprising: at least three cavities having at least three respective shapes, the at least three cavities opening from at least one of a first X_1-Y_1 surface of a metal block and an opposing second X_2-Y_2 surface of the metal block, the at least three cavities comprising: a first cavity having a first opening in a first Y-Z plane and a second opening in a second Y-Z plane that is offset from the first Y-Z plane by a first length along an X axis; a second cavity sharing the second opening in the second Y-Z plane with the first cavity, the second cavity having a third opening in a third Y-Z plane that is offset from the second Y-Z plane by a second length along the X axis, the second cavity having at least two heights and at least two widths; and a last cavity sharing a next-to-last opening in a next-to-last Y-Z plane with a next-to-last cavity, the last cavity having a last opening in a last Y-Z plane that is offset from the next-to-last Y-Z plane by a last length along the X axis, wherein the orthogonal waveguides are formed from the first cavity and the last cavity.

Example 2 includes the twist of Example 1, wherein the at least three cavities having the at least three respective shapes comprise four cavities having four respective shapes, wherein the at least two heights is at least two second-cavity heights, and wherein the at least two widths is at least two second-cavity widths, the twist further comprising: a third cavity sharing the third opening in the third Y-Z plane with the second cavity, the third cavity having a fourth opening in a fourth Y-Z plane that is offset from the third Y-Z plane by a third length along the X axis, the third cavity having at least two third-cavity heights and least two third-cavity widths, wherein the last cavity is a fourth cavity, and wherein sharing the next-to-last opening in the next-to-last Y-Z plane with the next-to-last cavity comprises sharing the fourth opening in the fourth Y-Z plane with the third cavity, and wherein the last cavity having the last opening in the last Y-Z plane comprises the fourth cavity having a fifth opening in a fifth Y-Z plane, the fifth Y-Z plane offset from the fourth Y-Z plane by a fourth length along the X axis.

Example 3 includes the twist of Example 2, wherein the at least two second-cavity heights includes three second-cavity heights in the second cavity along the Z axis, and wherein the at least two second-cavity widths includes three second-cavity widths in the second cavity along the Y axis, and wherein the least two third-cavity heights includes three third-cavity heights in the third cavity along a Z axis, and wherein the least two third-cavity widths includes three third-cavity widths in the third cavity along a Y axis.

Example 4 includes the twist of any of Examples 1-3, wherein a height along a Z axis of the first cavity is less than a height along a Z axis of the last cavity and a width along a Y axis of the first cavity is greater than a width along a Y axis of the last cavity, and wherein the height along the Z axis of the first cavity is about equal to the width along the Y axis of the last cavity and the height along the Z axis of the last cavity is about equal to the width along the Y axis of the first cavity.

Example 5 includes the twist of any of Examples 1-4, further comprising at least one metal cover attached to the at least one of the first X_1-Y_1 surface and the opposing second X_2-Y_2 surface, wherein the first cavity is one of an input waveguide or an output waveguide while the last cavity is a respective one of the output waveguide or the input waveguide.

Example 6 includes the twist of any of Examples 1-5, further comprising at least one metal cover attached to the at least one of the first X_1-Y_1 surface and the opposing second X_2-Y_2 surface, wherein the first opening in the first Y-Z plane is one of an input to an input waveguide or an output to an output waveguide while the last opening in the last Y-Z plane is a respective one of the output to an output waveguide or an input to an input waveguide.

Example 7 includes the twist of any of Examples 1-6, wherein the at least two heights includes three heights along a Z axis in the second cavity, and wherein the at least two widths includes three widths in the second cavity along a Y axis.

Example 8 includes the twist of any of Examples 1-7, further comprising a dielectric material in at least one of the second cavity and the next-to-last cavity.

Example 9 includes a method to form a twist for coupling electro-magnetic radiation between orthogonal waveguides, the method comprising: forming a first cavity having a first shape in a first X_1-Y_1 surface of a metal block, the first cavity having a first opening in a first Y-Z plane and a second opening in a second Y-Z plane that is offset from the first Y-Z plane by a first length along an X axis; forming a second cavity having a second shape in at least one of the first X_1-Y_1 surface of the metal block and an opposing second X_2-Y_2 surface of the metal block, the second cavity sharing the second opening in the second Y-Z plane with the first cavity, the second cavity having a third opening in a third Y-Z plane that is offset from the second Y-Z plane by a second length along the X axis, the second cavity having at least two heights and at least two widths; and forming a last cavity having a last shape in at least one of the first X_1-Y_1 surface of the metal block and the opposing second X_2-Y_2 surface of the metal block, the last cavity having a last opening in a last Y-Z plane that is offset from a next-to-last Y-Z plane by a last length.

Example 10 includes the method of Example 9, wherein the at least two heights is at least two second-cavity heights, and wherein the at least two widths is at least two second-cavity widths, the method further comprising: forming a third cavity having a third shape in at least one of the first X_1-Y_1 surface and the opposing second X_2-Y_2 surface, the third cavity sharing the third opening in the third Y-Z plane with the second cavity, the third cavity having a fourth opening in a fourth Y-Z plane that is offset from the third Y-Z plane by a third length along the X axis, the third cavity having at least two third-cavity heights and least two third-cavity widths.

Example 11 includes the method of Example 10, wherein forming the last cavity having the last shape comprises: forming a fourth cavity having a fourth shape, the fourth cavity sharing a fourth opening in a fourth Y-Z plane with a third cavity, the fourth cavity having a fifth opening in a fifth Y-Z plane, the fifth Y-Z plane offset from the fourth Y-Z plane by a fourth length.

Example 12 includes the method of any of Examples 10-11, wherein forming the third cavity having the third shape comprises: forming the third cavity with three third-cavity heights along the Z axis; and forming the third cavity with three third-cavity widths along a Y axis.

Example 13 includes the method of any of Examples 10-12, further comprising: positioning a dielectric material in the third cavity.

Example 14 includes the method of any of Examples 9-13, further comprising: positioning a dielectric material in the second cavity.

Example 15 includes the method of any of Examples 9-14, wherein forming the first cavity having the first shape and forming the last cavity having the last shape comprises: forming a first height along a Z axis of the first cavity to be approximately equal to a last width of the last cavity along a Y axis of the last cavity; and forming a last height along a Z axis of the last cavity to be approximately equal to a first width of the first cavity along a Y axis of the first cavity.

Example 16 includes the method of any of Examples 9-15, further comprising: positioning a dielectric material in the second cavity.

Example 17 includes a switched line phase shifter comprising: a first twist comprising at least a first cavity and a second cavity, the first cavity and the second cavity having at least two respective shapes, the first cavity and the second cavity opening from at least one of a first X_1-Y_1 surface of a metal block and an opposing second X_2-Y_2 surface of the metal block; a second twist comprising at least a third cavity and a fourth cavity, the third cavity having the shape of the second cavity, the fourth cavity having the shape of the first cavity, the third cavity and the second cavity opening from at least one of the first X_1-Y_1 surface of the metal block and the opposing second X_2-Y_2 surface of the metal block; a first connecting cavity coupling electro-magnetic radiation propagating along an X axis between the first twist and the second twist, wherein the first twist, the second twist, and the first connecting cavity open from at least one of the first X_1-Y_1 surface of the metal block and the opposing second X_2-Y_2 surface of the metal block; and at least one metal cover attached to at least the first X_1-Y_1 surface of the metal block.

Example 18 includes the switched line phase shifter of Example 17, further comprising: a third twist comprising at least a fifth cavity and a sixth cavity, the fifth cavity and the sixth cavity having at least two respective shapes, the fifth cavity and the sixth cavity opening from at least one of a first X_1-Y_1 surface of the metal block and an opposing second X_2-Y_2 surface of the metal block; a fourth twist comprising at least a seventh cavity and an eighth cavity, the seventh cavity having the shape of the sixth cavity rotated 180 degrees about a Z axis, the seventh cavity and the eighth cavity opening from at least one of the first X_1-Y_1 surface of the metal block and the opposing second X_2-Y_2 surface of the metal block; and a second connecting cavity coupling electro-magnetic radiation propagating along the X axis between the third twist and the fourth twist, wherein the third twist, the fourth twist, and the second connecting cavity open from at least one of the first X_1-Y_1 surface of the metal block and the opposing second X_2-Y_2 surface of the metal block, wherein electro-magnetic radiation propagating along the X axis from the third twist to the fourth twist is output from the fourth twist 180 degrees out of phase with electro-magnetic radiation propagating along the X axis from the first twist to the second twist that is output from the second twist.

Example 19 includes the switched line phase shifter of Example 18, further comprising: a ninth cavity in the first twist; a tenth cavity in the second twist; a eleventh cavity in the third twist; a twelfth cavity in the fourth twist, the eleventh cavity having the shape of the twelfth cavity rotated 180 degrees about a Z axis.

Example 20 includes the switched line phase shifter of any of Examples 18-19,

further comprising: a first switch arranged to one of output or input electro-magnetic radiation to or from one of the first twist and the third twist; and a second switch arranged to respectively one of input or output electro-magnetic radiation from or to one of the second twist and the fourth twist

A number of embodiments of the invention defined by the following claims have been described. Nevertheless, it will be understood that various modifications to the described embodiments may be made without departing from the spirit and scope of the claimed invention. Accordingly, other embodiments are within the scope of the following claims.

What is claimed is:

1. A twist for coupling electro-magnetic radiation between orthogonal waveguides, the twist comprising:

at least three cavities formed in a single metal block having at least three respective shapes, the at least three cavities opening from at least one of a first X_1-Y_1 surface of the metal block and an opposing second X_2-Y_2 surface of the metal block, the at least three cavities comprising:

a first cavity having a first opening in a first Y-Z plane of the metal block and a second opening in a second Y-Z plane that is offset from the first Y-Z plane by a first length along an X axis;

a second cavity sharing the second opening in the second Y-Z plane with the first cavity, the second cavity having a third opening in a third Y-Z plane that is offset from the second Y-Z plane by a second length along the X axis, the second cavity having at least two heights and at least two widths; and

a last cavity sharing a next-to-last opening in a next-to-last Y-Z plane with a next-to-last cavity, the last cavity having a last opening in a last Y-Z plane of the metal block that is offset from the next-to-last Y-Z plane by a last length along the X axis,

wherein the orthogonal waveguides are formed from the first cavity and the last cavity.

2. The twist of claim **1**, wherein the at least three cavities having the at least three respective shapes comprise four cavities having four respective shapes, wherein the at least two heights is at least two second-cavity heights, and wherein the at least two widths is at least two second-cavity widths, the twist further comprising:

a third cavity sharing the third opening in the third Y-Z plane with the second cavity, the third cavity having a fourth opening in a fourth Y-Z plane that is offset from the third Y-Z plane by a third length along the X axis, the third cavity having at least two third-cavity heights and least two third-cavity widths,

wherein the last cavity is a fourth cavity, and wherein sharing the next-to-last opening in the next-to-last Y-Z plane with the next-to-last cavity comprises sharing the fourth opening in the fourth Y-Z plane with the third cavity, and wherein the last cavity having the last opening in the last Y-Z plane comprises the fourth cavity having a fifth opening in a fifth Y-Z plane, the fifth Y-Z plane offset from the fourth Y-Z plane by a fourth length along the X axis.

3. The twist of claim **2**, wherein the at least two second-cavity heights includes three second-cavity heights in the second cavity along the Z axis, and wherein the at least two second-cavity widths includes three second-cavity widths in the second cavity along the Y axis, and wherein the least two third-cavity heights includes three third-cavity heights in the third cavity along a Z axis, and wherein the least two third-cavity widths includes three third-cavity widths in the third cavity along a Y axis.

4. The twist of claim **1**, wherein a height along a Z axis of the first cavity is less than a height along a Z axis of the last cavity and a width along a Y axis of the first cavity is greater than a width along a Y axis of the last cavity, and wherein the height along the Z axis of the first cavity is about equal to the width along the Y axis of the last cavity and the height along the Z axis of the last cavity is about equal to the width along the Y axis of the first cavity.

5. The twist of claim **1**, further comprising at least one metal cover attached to the at least one of the first X_1-Y_1 surface and the opposing second X_2-Y_2 surface, wherein the first cavity is one of an input waveguide or an output waveguide while the last cavity is a respective one of the output waveguide or the input waveguide.

6. The twist of claim **1**, further comprising at least one metal cover attached to the at least one of the first X_1-Y_1 surface and the opposing second X_2-Y_2 surface, wherein the first opening in the first Y-Z plane is one of an input to an input waveguide or an output to an output waveguide while the last opening in the last Y-Z plane is a respective one of the output to an output waveguide or an input to an input waveguide.

7. The twist of claim **1**, wherein the at least two heights includes three heights along a Z axis in the second cavity, and wherein the at least two widths includes three widths in the second cavity along a Y axis.

8. The twist of claim **1**, further comprising a dielectric material in at least one of the second cavity and the next-to-last cavity.

9. A method to form a twist for coupling electro-magnetic radiation between orthogonal waveguides, the method comprising:

forming a first cavity having a first shape in a first X_1-Y_1 surface of a metal block, the first cavity having a first opening in a first Y-Z plane of the metal block and a second opening in a second Y-Z plane that is offset from the first Y-Z plane by a first length along an X axis;

forming a second cavity having a second shape in at least one of the first X_1-Y_1 surface of the metal block and an opposing second X_2-Y_2 surface of the metal block, the second cavity sharing the second opening in the second Y-Z plane with the first cavity, the second cavity having a third opening in a third Y-Z plane that is offset from the second Y-Z plane by a second length along the X axis, the second cavity having at least two heights and at least two widths; and

forming a last cavity having a last shape in at least one of the first X_1-Y_1 surface of the metal block and the opposing second X_2-Y_2 surface of the metal block, the last cavity having a last opening in a last Y-Z plane of the metal block that is offset from a next-to-last Y-Z plane by a last length.

10. The method of claim **9**, wherein the at least two heights is at least two second-cavity heights, and wherein the at least two widths is at least two second-cavity widths, the method further comprising:

forming a third cavity having a third shape in at least one of the first X_1-Y_1 surface and the opposing second X_2-Y_2 surface, the third cavity sharing the third opening in the third Y-Z plane with the second cavity, the third cavity having a fourth opening in a fourth Y-Z plane that is offset from the third Y-Z plane by a third length along the X axis, the third cavity having at least two third-cavity heights and least two third-cavity widths.

11. The method of claim **10**, wherein forming the last cavity having the last shape comprises:

forming a fourth cavity having a fourth shape, the fourth cavity sharing a fourth opening in a fourth Y-Z plane with a third cavity, the fourth cavity having a fifth opening in a fifth Y-Z plane, the fifth Y-Z plane offset from the fourth Y-Z plane by a fourth length.

12. The method of claim **10**, wherein forming the third cavity having the third shape comprises:

forming the third cavity with three third-cavity heights along the Z axis; and

forming the third cavity with three third-cavity widths along a Y axis.

13. The method of claim **10**, further comprising:

positioning a dielectric material in the third cavity.

14. The method of claim **9**, further comprising:

positioning a dielectric material in the second cavity.

15. The method of claim **9**, wherein forming the first cavity having the first shape and forming the last cavity having the last shape comprises:

forming a first height along a Z axis of the first cavity to be approximately equal to a last width of the last cavity along a Y axis of the last cavity; and

forming a last height along a Z axis of the last cavity to be approximately equal to a first width of the first cavity along a Y axis of the first cavity.

16. The method of claim **15**, further comprising:

positioning a dielectric material in the second cavity.

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